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ELECTROSTATIC CHARGING IN RETICULATED FOAM

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Thornton Research Centre
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Experiments were carried out to determine the effect of a number of parameters on electrostatic charging inside reticulated-foam-filled aircraft fuel tanks during refueling operations. Tests with anti-static additives showed that a fuel conductivity of approximately 50 pS/m is sufficient to suppress all sparking provided fuel systems are designed so that fuel with a high discharge velocity is not directed into the foam.

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ELECTROSTATIC CHARGING IN RETICULATED FOAM: FINAL REPORT

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SUMMARY

A number of fires have occurred during the refuelling of aircraft tanks filled with reticulated foam. These incidents were almost certainly caused by electrostatic discharges, resulting from the foam acquiring an electrical charge owing to the passage of fuel. A series of tests have been carried out to examine the effect on charging of a variety of parameters, including foam type, inlet nozzle type, filling rate and discharge velocity, fuel type, additive content, water content and fuel temperature. Furthermore, the minimum conductivity required (produced by the addition of an antistatic additive) to suppress all sparking was determined for a variety of tank configurations and filling conditions. Two additives were evaluated, Shell ASA-3 and duPont Stadis 450. Most of the tests were carried out on a large-scale rig which incorporated a 400-litre simulated aircraft tank.

Polyether urethane foam (designated blue) was found to be intrinsically more hazardous than polyester urethane foam (designated red or orange). Under identical test conditions the polyether foam gave charging currents up to 18 times greater than those from the polyester foam. Furthermore, the blue foam has a conductivity an order of magnitude lower than that of the red and the orange foams.

The rate of charge generation was found to increase with both filling rate and discharge velocity, and results showed that systems should

be designed so that fuel with a high discharge velocity is not directed into reticulated foam. In tests with a single-orifice, high-velocity inlet and electrostatically active fuel, some sparking still occurred at a conductivity of 190 pS m^{-1} when the fuel was discharged into blue foam. The piccolo multi-orifice inlet was intrinsically the safest nozzle evaluated. Only in a very small number of tests with this device were hazardous discharges recorded, demonstrating further the importance of minimizing discharge velocity.

Of the various additives evaluated, the corrosion inhibitor Hitec E-515 was found to be the most electrostatically active and capable of significantly increasing charging.

In tests with electrostatically "hot" fuel and fine blue foam, a conductivity of 20 pS m^{-1}, produced by progressive additions of ASA-3, was sufficient to suppress all sparking with the piccolo inlet and also with a showerhead nozzle of the type found on F5-E aircraft. With the single-orifice inlet, where fuel was discharged against the tank wall, a conductivity of 39 pS m^{-1} was required. In tests with the showerhead nozzle and Stadis 450, a conductivity of 37 pS m^{-1} was needed to suppress all sparking. These results indicate that if a system is correctly designed a minimum conductivity of 50 pS m^{-1} (at ambient temperature) will provide adequate protection against electrostatically produced explosions. Finally, results from tests with the piccolo inlet indicated that a "hot" fuel, made safe at ambient temperature by the addition of ASA-3, will not constitute a hazard at temperatures at least as low as -15°C.

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ELECTROSTATIC CHARGING IN RETICULATED FOAM: FINAL REPORT

1. INTRODUCTION

The fuel tanks of some military aircraft are filled with reticulated polyurethane foam to prevent the explosive propagation of flames when the tank is penetrated by an incendiary bullet. Since 1974 the US Air Force has experienced eight fuel tank fires when refuelling aircraft equipped with this material. However, in each case only minor damage was sustained because the foam prevented the propagation of an explosion. Subsequent work has shown that these incidents were almost certainly caused by electrostatic discharges.

Electrostatic charging can occur in a variety of situations where petroleum distillates are pumped, e.g. when flowing through a pipe[1] and, to a greater extent, through a microporous filter.[2,3] Charging arises from the presence in the fuel of minute traces of ionisable contaminant. Preferential adsorption of ions of one polarity on the walls of the pipe or on the fibres of the microfilter means that the flowing liquid carries a net charge and hence constitutes a streaming current. In the latter case this can be some tens of microamperes. The reticulated foam behaves like a coarse filter and acquires a charge due to the passage of fuel. Furthermore, because it is a polymeric material, the foam has a high electrical resistivity and can retain that charge for a significant period. Thus, when filling tanks packed with reticulated foam, a build-up of charge on the foam and in the fuel can occur. Hence an electric field will be created inside the tank, the field strength being highest at the surface of earthed metal protrusions, e.g., the inlet nozzle or metal fuel pipes crossing the tank. If the field strength at the protrusion should reach a value of 3000 kV m^{-1}, then a "brush"-type discharge will occur. Such discharges are characterised by a concentrated hot core that extends a few millimetres from the earthed protrusion before splitting into numerous less luminous tracks that fan out towards the charged foam and/or fuel. If the discharge should pass through a region where a flammable mixture is present, and if the discharge should release an amount of energy that exceeds a critical value, then an ignition will occur.

With a view to formulating safe filling criteria and improving the design of fuel systems incorporating reticulated polyurethane foam, the US Air Force sponsored several in-house and contract research projects. Shell Research Ltd. were given one of these contracts, and this report discusses the results of the work.

The aim of the programme was to examine the effect on charging in polyurethane foam of a variety of parameters, including foam type, inlet nozzle type, filling rate and discharge velocity, fuel type, additive content, water content and fuel temperature. A number of tests with antistatic additives were also carried out to determine the level of conductivity necessary to suppress discharges during tank filling.

This report is arranged so that Sections 2-4 give a self-contained summary of the work, together with the main conclusions, and the Appendices give experimental details and a detailed discussion of the results.

2. DESCRIPTION OF TESTS

2.1 Test facilities

Most of the experimental work was done on two test rigs, a small-scale charging-tendency rig and a large-scale tank-filling rig.

2.1.1 Small-scale charging-tendency rig

The use of this apparatus was necessary to expedite the evaluation of all the additives and foams specified in the contract. The layout of the rig is shown in Figure 1. The test fuel was circulated from the reservoir tank through the sample of foam being evaluated and back to the reservoir via a flowmeter. The foam sample was cylindrical, having a diameter of 20 mm and a length of 100 mm, and was contained within a steel tube which was electrically isolated from the rest of the system and connected to ground through a Keithley electrometer. As fuel passed through the foam, charge separation occurred and a current was induced through the electrometer. The magnitude of this current gave a measure of the charging tendency of the fuel/foam combination under examination. A flow rate of 0.25 litre s^{-1} was used, giving a linear fuel velocity through the foam of 0.8 m s^{-1}, which was of the same order as the average fuel velocity through the foam in the large-scale tank-filling tests with the single-orifice inlet (see Section 2.2). The reservoir had a capacity of 30 litres and, over the range of conductivities examined, this gave adequate time for charge to relax from the fuel before the latter was re-circulated through the foam.

2.1.2 Large-scale tank-filling rig (see Plate I)

Fuel was pumped from the open tank, through a 500-litre relaxation tank (to allow charge generated by the pump to dissipate), a wire mesh strainer (to remove particulate matter) and into the foam-filled simulated aircraft tank. This had a capacity of 400 litres and a depth of 650 mm. However, in the tests, the tank was filled to a height of only 500 mm to prevent fuel splashing over the sides, the tank being open. The position of the tank and the pipework could be varied to accept different types of inlet nozzles. After completing a filling test the fuel was drained into the open tank.

To quantify the hazard presented by a particular tank configuration with a particular set of filling conditions, the following measuring techniques were used:

(i) The number and magnitude of any sparks occurring to the inlet nozzle assembly during a test were determined, earlier work[4] having shown that sparking to the inlet nozzle was the preferred mechanism in the absence of other earthed components inside the tank. Spark magnitudes were measured by electrically isolating the nozzle from the rest of the system and connecting it to ground via an RC network. Noting the voltage rise produced on the capacitor by a spark allowed the total charge transferred in the discharge to be determined (for more details see Appendix B.1). Studies of liquid-to-metal discharges[5,6] indicate that spark-charge transfers in excess of -75 nC or +150 nC can ignite stoicheiometric alkane/air mixtures.

A spark was therefore classified as hazardous if its magnitude exceeded either of these limits.

(ii) Isolating the nozzle also allowed measurements of the current induced to it by the electric field created by the charged foam. As discussed in Appendix B.1, this current reached a maximum value immediately after filling commenced, thereafter decreasing with time. The size of the current peak was directly related to the rate of charge generation, and this could then be used to compare the effects of certain parameters. This technique was particularly useful in the early tests with clean fuel. In the later tests with more active fuel, the induction current was swamped by currents from other sources, notably conduction to the nozzle from charged fuel.

(iii) The electric field above the tank was measured with a rotating-vane fieldmeter, positioned as shown in Figure 2. As the field was a function of various parameters, e.g. the magnitude and spatial and temporal distribution of the charge in the fuel and on the foam, and on the inlet nozzle type, it could be used only as a qualitative measure of the degree of charging in a particular test.

(iv) A low-light-level camera system, sensitive down to light intensities equivalent to starlight, was used in some tests to observe the discharges.

2.2 Scope

The effects of the following parameters on charging were examined:

2.2.1 Foam type

Reticulated polyester urethane foam was originally used for the suppression of fuel-tank explosions. However, a new type of reticulated foam, a polyether urethane formulation, has been developed to replace the polyester foam. The new material is highly resistant to hydrolytic instability and is projected to have a significantly improved service life.

Small-scale tests carried out prior to this work[7] indicated that the new foam is a significantly more active charge generator than the polyester foam. Furthermore, its electrical resistivity was found to be an order of magnitude higher, as confirmed by the tests described in Appendix A.1. The new foam is therefore intrinsically more hazardous.

Two samples of polyester and two samples of polyether foam were evaluated, the former being red (25 pores per inch) and orange (10 pores per inch) foam and the latter being fine blue (25 pores per inch) and coarse blue (15 pores per inch) foam. Some tests were also carried out with a new type of foam that has been developed by ICI Ltd. This foam has a nylon formulation and is called Promel.

2.2.2 Nozzle type

Three different inlet nozzles were tested and, with reference to Plate II, they comprised:

(i) A single-orifice inlet, similar to the type installed in the forward tanks of the first 210 A-10 aircraft to be built.

(ii) A piccolo nozzle, as installed in the forward tanks of all A-10 aircraft built after number 210. Fuel was discharged through twenty-three 0.5-inch diameter holes in the bottom of the nozzle.

(iii) A showerhead-type nozzle, as installed on F5-E aircraft. The nozzle was fitted with a shroud to direct fuel vertically downwards.

Figure 2 shows how the nozzles were installed in the test tank and the various configurations of the void in the foam in the region around the inlet used in the test programme.

2.2.3 Filling conditions

Filling rates in the range 189-454 litre min^{-1} (50-120 USgal min^{-1}) and discharge velocities in the range 3.1-17.4 m s^{-1} (10-57 ft s^{-1}) were examined. In the case of the single-orifice inlet, altering the diameter of the orifice at the end of the nozzle allowed these parameters to be varied independently. This was not the case with the other two nozzle types examined, the sizes of their orifices being fixed. The maximum filling rate attainable with the Piccolo inlet was 341 litre min^{-1} (90 USgal min^{-1}), owing to the capacity of the pumping system.

2.2.4 Base fuels

Two base fuels, odourless kerosine and Jet A-1, were used in the tests, the former being used for all the work on the large-scale tank-filling rig.

In practice, charging is caused by the presence of trace quantities of naturally occurring contaminants, and so there is no such thing as a "typical fuel" in this context. In order to simulate the worst condition that could be encountered in the field, some filling tests were carried out with a base fuel (odourless kerosine) that had been made electrostatically "hot" by the addition of a procharger, a 1-decene polysulpnone. This compound was identified in earlier work at Thornton[8] and was found to be significantly more effective than Gulf Additive 178 (a corrosion inhibitor) as used by others[9] in their work on electrostatic charging in reticulated foam.

2.2.5 Additives

The charging properties of four corrosion inhibitor additives, Hitec E-515, Unicor J, DCI-4A and Apollo PRI-19, were examined, the additives being tested at their minimum and maximum recommended doping levels.[10] Fuel system icing inhibitor (FSII) as specified by MIL-I-27686 was evaluated and the effect of adding free water to the fuel was determined:

Table 1

Corrosion inhibitor concentrations

Additive	Min. effective conc., mg $litre^{-1}$	Max. allowed conc., mg $litre^{-1}$
Hitec E-515	21.43	45.71
Unicor J	8.57	22.85
DCI-4A	8.57	22.85
Apollo PRI-19	8.57	22.85

One means whereby hazardous discharges during tank filling can be suppressed is to increase the conductivity of the fuel by using an antistatic additive. Earlier work at Thornton[4] had indicated that the minimum safe conductivity level for foam-filled tanks was higher than that for normal aircraft systems. Furthermore, Shell ASA-3 was found to be significantly more effective than DuPont Stadis 450 in that a lower conductivity was required to suppress hazardous discharges during filling tests. In view of its wider scope, the present work therefore included a further series of antistatic additive doping tests. ASA-3 and Stadis 450 were evaluated, and both clean and electrostatically "hot" base fuels were used.

2.2.6 Fuel temperature

A number of tank filling tests were carried out in which the fuel temperature was varied. Temperatures in the range -15°C to +26°C were examined.

2.3 Test programme

Table 2 summarises the test programme. The small-scale charging tendency rig was used:

(i) to compare the relative charging tendencies of the various types of foam,

(ii) to determine the charging properties of the icing and corrosion inhibitors, and

(iii) to examine the dependence of these properties on the nature of the base fuel.

The remainder of the parameters listed in Section 2.2 were evaluated by means of a large number of tests with the tank-filling rig. These tests have been classified according to the type of fuel used and they are described in the order in which they were made. The first series was with odourless kerosine, which had been clay-treated to make it electrostatically clean (conductivity <1 pS m^{-1}). Red polyester and

Table 2

Test programme

Parameter	Small-scale tests on charging-tendency rig	Tank filling tests			
		Tests with clean fuel	Tests with fuel containing Hitec E-515 and FSII	Antistatic additive tests with clean fuel	Antistatic additive tests with "hot" fuel
Foam type: Red	X	X			
Foam type: Orange	X				
Foam type: Fine blue	X		X	X	X
Foam type: Coarse blue	X	X			
Foam type: Promel	X			X	
Nozzle type: Single orifice		X	X	X	X
Nozzle type: Piccolo			X	X	X
Nozzle type: Showerhead		X	X	X	X
Filling rate		X	X	X	X
Discharge velocity		X	X	X	X
Base fuel: Odourless kerosine	X	X	X	X	X
Base fuel: Jet A-1	X				
Charging properties of additives	X				
Effect of free water			X		
Fuel temperature			X		X

N.B. Crosses show parameters examined in each test series coarse blue polyether foams were evaluated, and the single-orifice and showerhead nozzles were tested; details of the piccolo inlet had not been supplied at that time. In the tests with the showerhead nozzle, fuel was discharged directly into the foam. However, in later tests with this inlet, fuel was discharged against the base of the tank and the void was widened to simulate the arrangement on the F5-E aircraft more closely.

The next series was with a simulated "real" fuel consisting of odourless kerosine containing icing inhibitor and Hitec E-515, small-scale tests having shown that the latter had the highest charging tendency of all the corrosion inhibitors examined. In this and in subsequent test series (apart from one test with Promel) fine blue polyether foam was used, small-scale tests having indicated that, of the types examined, this foam was the most active charge generator. The blue foam charged positively in all the tests. In order to minimise the impingement of fuel on foam, the single-orifice inlet was repositioned at the bottom of the test tank, as shown in Figure 2.

After completing the above tests, the fuel was clay-treated to remove the icing and corrosion inhibitors, and a series of antistatic additive doping tests was carried out. Both ASA-3 and Stadis 450 were evaluated. In the earlier work at Thornton[5] on reticulated foam there were several instances where adding small quantities of antistatic additive to fuel increased the number of hazardous discharges during a filling test. The first series of doping tests, therefore, were with a base fuel of odourless kerosine, clay-treated to render it electrostatically clean, in order to examine the charging properties of antistatic additives in fuel of low activity. Commencing at a low fuel conductivity (<5 pS m^{-1}) the additive undergoing evaluation was gradually added to the fuel until hazardous discharges to the nozzle under test during a filling operation ceased. The fuel was then clay-treated before proceeding. However, it was found to be extremely difficult to remove all traces of the additives, particularly ASA-3, and consequently the base fuel was significantly more active than in the work performed hitherto, and sparking was observed in many tests before additive addition. These tests were then repeated (fourth series) with an electrostatically "hot" fuel (odourless kerosine plus 1-decene polysulphone).

To determine the importance of fuel temperature, the whole tank-filling rig was moved into a "cold room", and a series of tests carried out with the piccolo inlet and fine blue foam. In the first instance the test fuel comprised odourless kerosine plus icing inhibitor and Hitec E-515. Then a test was carried out to determine if a "hot" fuel, made safe at ambient temperature by the addition of ASA-3, could represent a hazard at low temperature owing to the subsequent reduction in ion mobilities causing the ASA-3 to be less effective.

Finally, the effect of free water in the fuel was examined. These tests were made with the piccolo inlet, fine blue foam, and odourless kerosine as the base fuel. The water was pre-emulsified with a sample of fuel and the resulting mixture injected in parallel with the test fuel during each tank filling operation from a tube positioned alongside the piccolo nozzle. This somewhat complicated procedure had to be followed because of the ease with which the odourless kerosine shed free water.

3. RESULTS AND DISCUSSION

3.1 Tests with charging-tendency rig

(Details in Appendix A.2)

Two series of tests were carried out, one with a base fuel of clay-treated odourless kerosine (conductivity <0.5 pS m^{-1}) and the other with a base fuel of Jet A-1. The latter was obtained directly from a refinery and consequently was additive-free. The charging tendency of the icing and corrosion inhibitors in each base fuel on all four polyurethane foams was determined. The corrosion inhibitors were evaluated individually in the presence of icing inhibitor, a new sample of base fuel being used for each test.

The results from the tests with odourless kerosine are shown in Figure 3, the magnitude of the charging current (measured one minute after flow commenced, to allow equilibrium to be established) being a measure of the charging tendency of the fuel/foam combination under test. The results obtained are presented for the particular foam/fuel/additive combination at the minimum and maximum recommended doping levels for the additive. Although the results were to some extent influenced by the activity of the samples of base fuel used in each test, which did vary (see Appendix A2), the following conclusions can be drawn:

(i) The blue polyether foams always charged positively (the polarity of the foam being the same as the sign of the charging current), whereas the charging polarity of the red and orange polyester foams varied.

(ii) The currents from the fine and coarse blue foams were, on average, a factor of 9 and 5 greater, respectively, than the modulus of the current from the red foam under identical test conditions.

(iii) The addition of corrosion inhibitor always increased charging, Hitec E-515 being the most active, producing charging currents an order of magnitude greater than those of any other additive.

(iv) The charging current was a function of porosity for both types of foam, the magnitude of the current being directly related to the number of pores per inch in each case. These results do not agree with those obtained by Leonard et al[7] from tests with uncompressed foam samples.

The results from the tests with Jet A-1 are shown in Figure 4. In this case the activity of the base fuel, which was significantly higher than that of the odourless kerosine, had a major influence on the results. The conductivity of the fuel was also higher, being in the range 5.9-10 pS m^{-1}. However, the variation in the activity of the samples of base fuel was significantly smaller than in the tests with odourless kerosine, and the main observations are as follows:

(i) Apart from two exceptions, all foams charged positively, which was caused primarily by the intrinsic charging properties of the base fuel. In the case of the red and orange foams, Unicor J and Apollo PRI-19 acted to reduce the degree of positive charging, but only Hitec E-515 was able to make these foams charge negatively.

(ii) An interesting feature of the tests was the magnitude of the currents generated by the fine and coarse blue foams relative to the corresponding red foam current, being 2.7 and 1.7 on average, respectively, compared to 9 and 5 in the odourless kerosine tests.

(iii) The charging tendency of Apollo PRI-19-treated fuel, with all foams, was significantly lower than that of untreated Jet A-1. Furthermore, the addition of Apollo PRI-19 resulted in a reduction of the fuel's conductivity. These results were not observed in the previous test series.

(iv) The combination of Hitec E-515 and fine blue foam produced the highest charging currents recorded, which, however, did not exceed the currents recorded in the corresponding tests with odourless kerosine.

(v) The relationship between charging and porosity was confirmed.

Finally, samples of ICI Promel were also evaluated using a fuel consisting of Jet A-1 containing icing inhibitor and DCI-4A at the maximum recommended concentration. The Promel foam was found to have a charging tendency between that of red foam and that of coarse blue foam. The charging tendency increased with sample density.

3.2 Tests with tank-filling rig

3.2.1 Tests with "clean" fuel
(Details in Appendix B.2)

In all the tests with clean fuel, both of the foams evaluated, red polyester and coarse blue polyether, charged positively.

Sparking was not observed in the tests with the single-orifice inlet and red foam, and the conductivity of the fuel remained constant at 0.85 pS m^{-1}. Upon completion of the work with red foam, the tank was re-filled with coarse blue foam and a number of tests were carried out to determine the effect of inlet velocity on charging. The system was then left to stand for two days, after which the conductivity of the fuel was found to have risen to 1.2 pS m^{-1}. Frequent sparking to the inlet nozzle was observed in subsequent tests, some of the sparks having magnitudes in excess of +250 nC - well above the incendive threshold. The fuel was therefore clay-treated before proceeding; again sparking was not observed in this course of tests with the single-orifice inlet, although the conductivity of the fuel gradually increased. These observations suggest that the fuel absorbed some pro-charging substance from the blue foam.

In the tests with the showerhead nozzle, considerable sparking was observed in the initial tests with coarse blue foam. The sparks were to the inlet pipe and had magnitudes well below the incendive threshold. Although clay-treating the fuel in the first instance actually increased the total number of discharges during a test, after further test runs sparking stopped altogether, possibly owing to the removal of some active component from the fuel.

The following observations are common to the work carried out with both nozzle types.

(i) The rate of charge generation increased with inlet velocity and filling rate.

(ii) The rate of charge generation with coarse blue foam was, on average, a factor of 6 greater than with red foam under indentical test conditions. This is in good agreement with the results from the small-scale tests with odourless kerosine, and with the results obtained by Leonard et al.[7]

3.2.2 Tests with odourless kerosine containing FSII and Hitec E-515 (Details in Appendix B.3)

In the tests with odourless kerosine described above, sparking was intermittent and could not be used to quantify the hazard presented by a particular tank configuration. By adding FSII and Hitec E-515 to the fuel it was hoped that more consistent sparking would be obtained.

However, rather surprisingly, discharges were observed only in the tests with the piccolo nozzle. The sparks occurred in the latter stages of each test and were from the fuel to the vertical stem of the inlet nozzle. As the fuel charged negatively, the sparks recorded corresponded to the transfer of negative charge. Increasing the filling rate increased the magnitude of the discharges; however, at the maximum filling rate attainable, 341 litre min^{-1} (90 USgal min^{-1}), they were still non-incendive.

In the tests with the single orifice inlet and coarse blue foam described in Section 3.2.1, potentially incendive discharges were observed in some instances. The fact that such phenomena were not observed in the tests discussed here suggests that repositioning the nozzle at the base of the tank reduced the hazard relative to the situation where the nozzle was on a level with the centre of the tank (as in the previous tests).

3.2.3 Antistatic additive doping tests with "clean" base fuel (Details in Appendix B.4)

Considering the results obtained with the three nozzle types separately:

(i) Tests with the single-orifice inlet. These tests were carried out solely with ASA-3. Sparking was observed when fuel was discharged directly into a block of fine blue foam positioned in front of the nozzle (see Figure 2) but not when the fuel was discharged against the tank wall. Subsequent tests showed that these discharges were not in fact to the nozzle but from the region of foam opposite the nozzle to other regions in the tank, and thus estimating their magnitudes from the corresponding nozzle signals provided only lower limits on their sizes (see Appendix B.5). However, this was not realised at the time and it was assumed that the observed sparks were from the charged fuel to the nozzle, the discharges apparently being non-incendive. In view of the latter, the test was terminated when the fuel conductivity reached 80 pS m^{-1}, even though the discharges still occurred.

These results demonstrate the importance of not directing fuel with a high discharge velocity into the foam.

(ii) Test with the showerhead inlet. The results from the tests with ASA-3 and Stadis 450 are plotted in Figure 5. In the tests where sparking was observed, discharges to both the inlet pipe and the nozzle assembly were detected, the former occurring in the early stages of the test and the latter during the end stages. In particular, some discharges occurred after filling was terminated, as the charged foamed fuel (created as a result of the turbulent conditions inside the tank and which enveloped the nozzle in the later stages of the test) collapsed. These discharges were observed to be between the walls of the void in the foam and the shroud around the nozzle assembly and were therefore of positive polarity. The sparks observed during the test were also mainly of positive polarity, and only occasionally were negative discharges recorded, presumably from the charged fuel.

Each conductivity test was carried out at two filling rates, 303 and 454 litre min^{-1} (80 and 120 USgal min^{-1}). However, there was no significant difference between the results from the tests at different filling rates, and the results from the individual tests performed at a particular conductivity have therefore been averaged to give the values plotted in Figure 5. A direct comparison between the results obtained with the two additives is difficult because the base fuels had very different activities. However, it is evident that a conductivity <20 pS m^{-1} was sufficient to suppress all sparking in both cases.

After completing these tests the tank was repacked with ICI Promel and a Stadis 450 doping test was then carried out. Rather surprisingly, sparking was observed only at a relatively high conductivity, 30 pS m^{-1}. However, the discharges were small and were well below the incendive threshold. These results on the relative hazards presented by Promel and fine blue foam are in qualitative agreement with those from the small-scale tests discussed in detail in Appendix A.2.

(iii) Tests with the piccolo inlet. Although sparking was observed in these tests between the charged fuel and the vertical stem of the inlet, the sparks did not reach incendive magnitudes, the largest discharge recorded having a magnitude of -66 nC. In the case of ASA-3, a conductivity of 8 pS m^{-1} was sufficient to suppress all sparking; in the case of Stadis 450 a conductivity of 19 pS m^{-1} was required.

3.2.4 Antistatic additive doping tests with "hot" fuel

(Details in Appendix 3.5)

These tests had the object of determining the conductivity level required to suppress hazardous sparking when the base fuel was highly electrostatically active. To produce such a fuel, varying amounts (0.04-0.18 ppm (w/v)) of 1-decene polysulphone were added to clay-treated odourless kerosine.

(i) Tests with the single-orifice inlet. These tests were carried out solely with ASA-3, as in the corresponding work with clean base fuel. A total of 0.077 ppm of polysulphone was added to the fuel, which raised the conductivity to 7.1 pS m^{-1}. At this level of activity, many incendive discharges were observed during each test, both when the fuel was directed into the foam and when the fuel was discharged against the tank wall opposite the nozzle. A study of these discharges with the camera system revealed that their bright roots were located on the foam and not, as with the other inlets tested, on the nozzle. As mentioned in Section 3.2.3, it was realised that estimating the sizes of these discharges from the corresponding nozzle signals provided only lower limits on their sizes. Even so, a number of discharges produced nozzle signals equivalent to charge transfers in excess of +750 nC and must have had magnitudes well above the incendive threshold. Progressive additions of ASA-3 to the fuel reduced the number of these discharges occurring per test. A conductivity of 39 pS m^{-1} was sufficient to suppress all sparking when fuel was directed against the tank wall. However, even at a conductivity of 190 pS m^{-1}, some sparking still occurred when the fuel was discharged directly into the foam, although the discharges were confined to a short period at the start of each test and were, most probably, non-incendive.

(ii) Tests with the showerhead nozzle. ASA-3 and Stadis 450 were evaluated and the results are plotted in Figure 6. In the former tests, polysulphone was added to the fuel until 30-35 potentially incendive discharges to the nozzle from the walls of the foam void occurred over the course of each test. The first addition of ASA-3 actually reduced the conductivity of the fuel from 5.9 to 3.6 pS m^{-1}, and a total of 0.11 ppm (w/v) of the additive had to be added to bring the conductivity up to its original level. Thereafter, progressive additions of ASA-3 reduced the frequency of incendive discharges, and a conductivity of 20 pS m^{-1} was sufficient to stop all sparking.

It was noted in the tests with ASA-3 that, at a particular conductivity, more incendive discharges occurred per test when a filling rate of 303 litre min^{-1} (80 USgal min^{-1}) was used than when a rate of 454 litre min^{-1} (120 USgal min^{-1}) was used. Consequently the tests with Stadis 450 were all done at the lower rate. Polysulphone was added until the activity of the fuel was similar to that of the base fuel used in the ASA-3 tests. The first two additions of Stadis 450 actually increased the number of incendive discharges per test; thereafter, further additions reduced the number until, at a conductivity of 37 pS m^{-1}, discharges were not detected.

(iii) Tests with the piccolo nozzle. Although a few incendive discharges were observed in tests immediately following the first addition of polysulphone, after a few tests sparking ceased and could not be made to occur again even though the fuel was made highly active by further additions of pro-charger. However, in the work to evaluate the effect of fuel temperature on charging (described in Section 3.2.5), these tests were repeated with new samples of fuel and foam. Incendive discharges were detected and the fuel's conductiity had to be raised to 18 pS m^{-1} by addition of ASA-3 to suppress these sparks. The difference between the results from the two tests with polysulphone could have stemmed from using new foam for the later work.

3.2.5 Low-temperature tests and tests to determine the effect of free water

(Details in Appendix B.6)

Owing to time limitations, only the piccolo nozzle was evaluated in these tests, which were all performed at a filling rate of 341 litre min^{-1} (90 USgal min^{-1}).

In the first low-temperature test, the base fuel was odourless kerosine containing FSII and Hitec E-515. Contrary to the results from earlier tests (Section 3.2.2) with this fuel/foam/nozzle combination, incendive discharges were observed at ambient temperature. This could have been related to the fact that new foam was installed prior to commencing these later tests. The effect on sparking of reducing the temperature is shown in Figure 7. The frequency of incendive discharges was not significantly affected by reducing the temperature, although the magnitude of the discharges increased gradually as the temperature fell.

The system was then allowed to return to ambient temperature. Further tests revealed that sparking had ceased and that the conductivity of the fuel had decreased from 5.1 to 3.3 pS m^{-1}. This indicated that some active component had been removed from the fuel. Polysulphone was then added to the fuel to increase its activity to a level where six incendive discharges were detected per test. The conductivity of the fuel was then increased to 18 pS m^{-1} by adding ASA-3. Sparking was not observed at this level of conductivity, and reducing the temperature to -15°C did not cause sparking to re-appear, even though the conductivity was reduced considerably. These results indicate that a fuel made safe at ambient temperature by addition of ASA-3, will also be safe at temperatures at least as low as -15°C.

For the tests with water, the base fuel was odourless kerosine containing FSII and Hitec E-515. Discharges were not observed in tests with the base fuel, and increasing the free water content of the fuel entering the tank up to a maximum value of 2460 ppm (v/v) did not initiate sparking, although electric field readings indicated that the rate of charge generation did increase somewhat with water content. However, the peak field readings were considerably lower than those measured in corresponding tests with polysulphone. These results indicate that water does not behave as a significant pro-charger with polyurethane foam.

4. CONCLUSIONS

These are listed under the sub-headings of the parameters to which they relate.

4.1 Foam type

(i) Blue polyether urethane foam is intrinsically more hazardous than red and orange polyester urethane foams.

(a) The conductivity of the former is an order of magnitude lower than that of the latter.

(b) Comparing foams of equal porosity, under identical test conditions, fine blue foam produced charging currents between 2 and 18 times greater than those produced by red foam.

(c) In some instances, the test fuel absorbed a pro-charger from the blue foam.

(ii) New foam can be a significantly more active charge generator than used foam.

(iii) For both foam types, the rate of charge generation increases with the number of pores per inch.

(iv) ICI Promel is intrinsically less hazardous than blue polyether foam. Promel has a charging tendency between that of red and coarse blue foam and a conductivity of the same order as that of the former material.

4.2 Nozzle type and filling conditions

(i) The rate of charge generation increases with filling rate and inlet velocity.

(ii) Systems should be designed so that high velocity fuel is not discharged directly into reticulated foam during tank filling. In tests with the single orifice inlet where electrostatically "hot" fuel was discharged into fine blue foam, some sparking still occurred at a fuel conductivity of 190 pS m^{-1}.

(iii) The piccolo nozzle was the intrinsically safest nozzle tested. Only in a very small number of tests with this inlet were hazardous discharges observed.

4.3 Base fuel and additive content

(i) Hitec E-515 was the most electrostatically active additive evaluated. Unicor-J and Apollo PRI-9 were the least active and did not significantly increase charging.

(ii) The charging tendency of Jet A-1 was significantly higher than that of clay-treated odourless kerosine.

(iii) In tests with the piccolo inlet, the presence of free water did not significantly increase charging.

4.4 Anti-static additives

(i) The table below shows the conductivites required with ASA-3 and Stadis 450 to suppress all sparking in the tests performed with fine blue polyether foam and both electrostatically clean and "hot" base fuel.

Table 3

Results from tests with antistatic additives

Nozzle	Conductivity, pS m^{-1}			
	Clean base fuel		"Hot" base fuel	
	ASA-3	Stadis 450	ASA-3	Stadis 450
Single-orifice (fuel discharged against tank wall)	No sparks observed	-	39	-
Showerhead	16	16	20	37
Piccolo	8	19	18	-

(ii) As indicated in Table 3 and by the results of the earlier work[4], ASA-3 was more efficient than Stadis 450 at making the system safe, in that a lower conductivity was required to suppress sparking.

4.5 Fuel temperature

(i) In the tests with the piccolo inlet, reducing the temperature of the fuel to -15°C did not give a significantly increased hazard.

(ii) Results indicated that an electrostatically hazardous fuel made safe at ambient temperature by the addition of ASA-3 will not present a hazard at temperatures down to at least -15°C.

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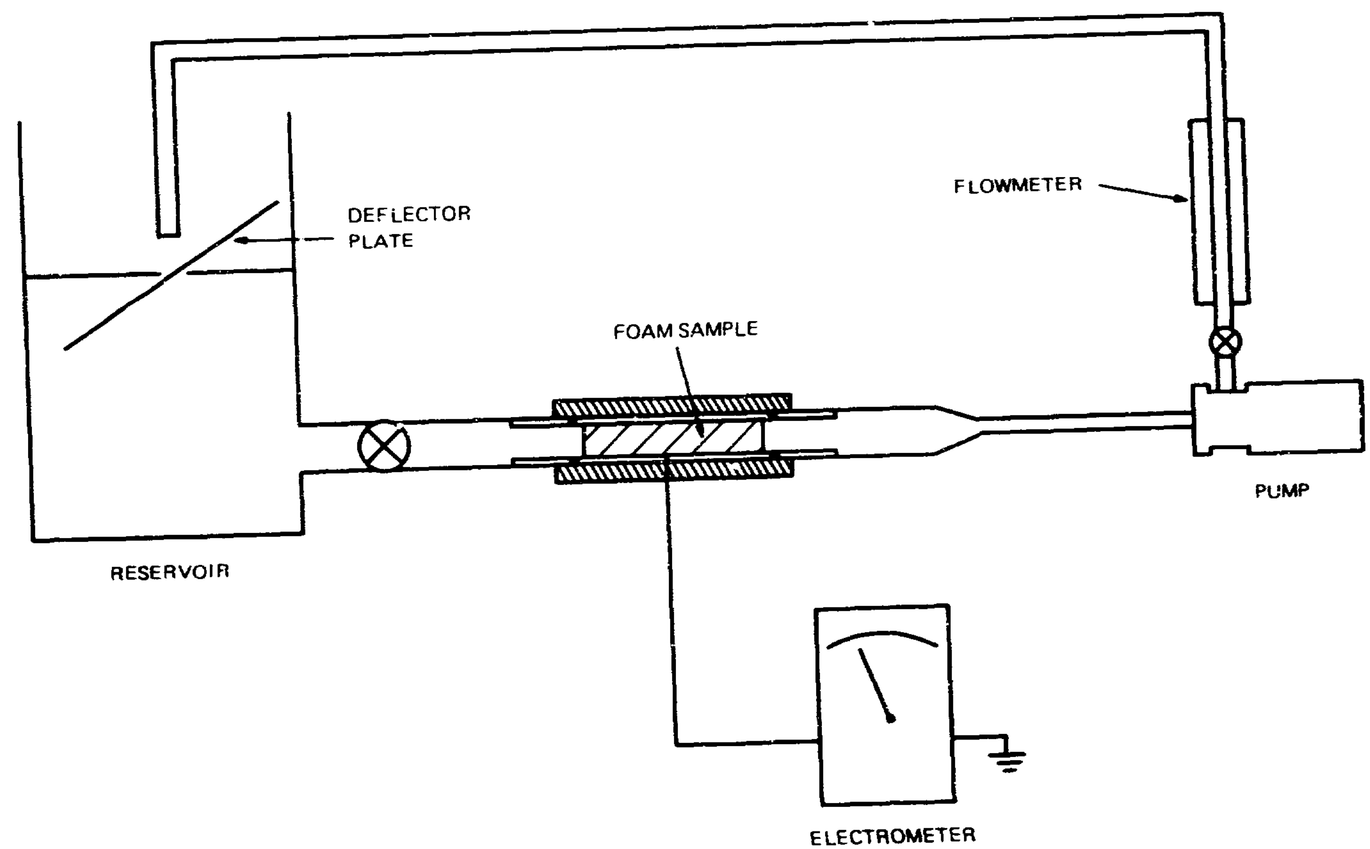


FIG. 1 — Charging-tendency rig

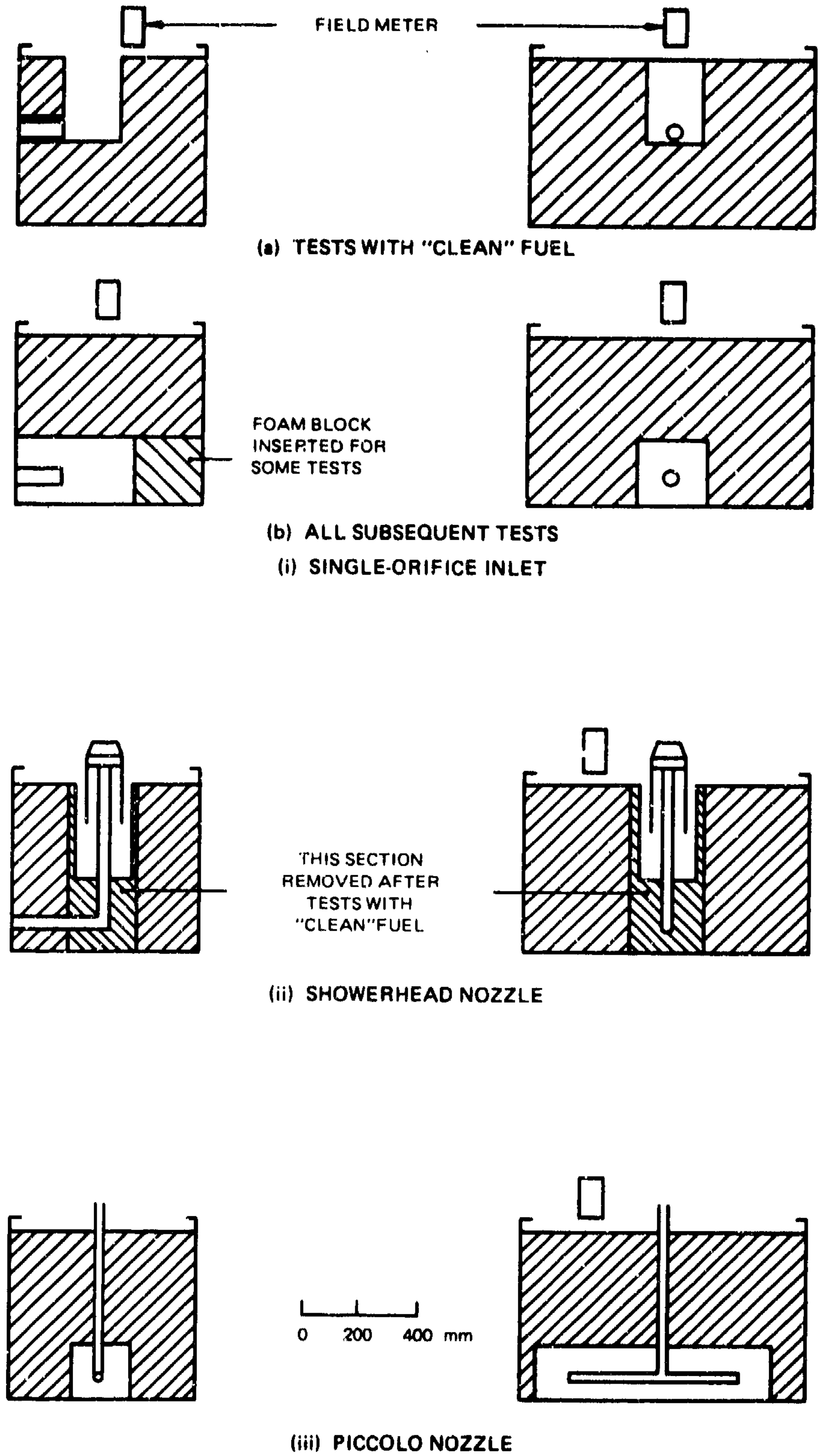
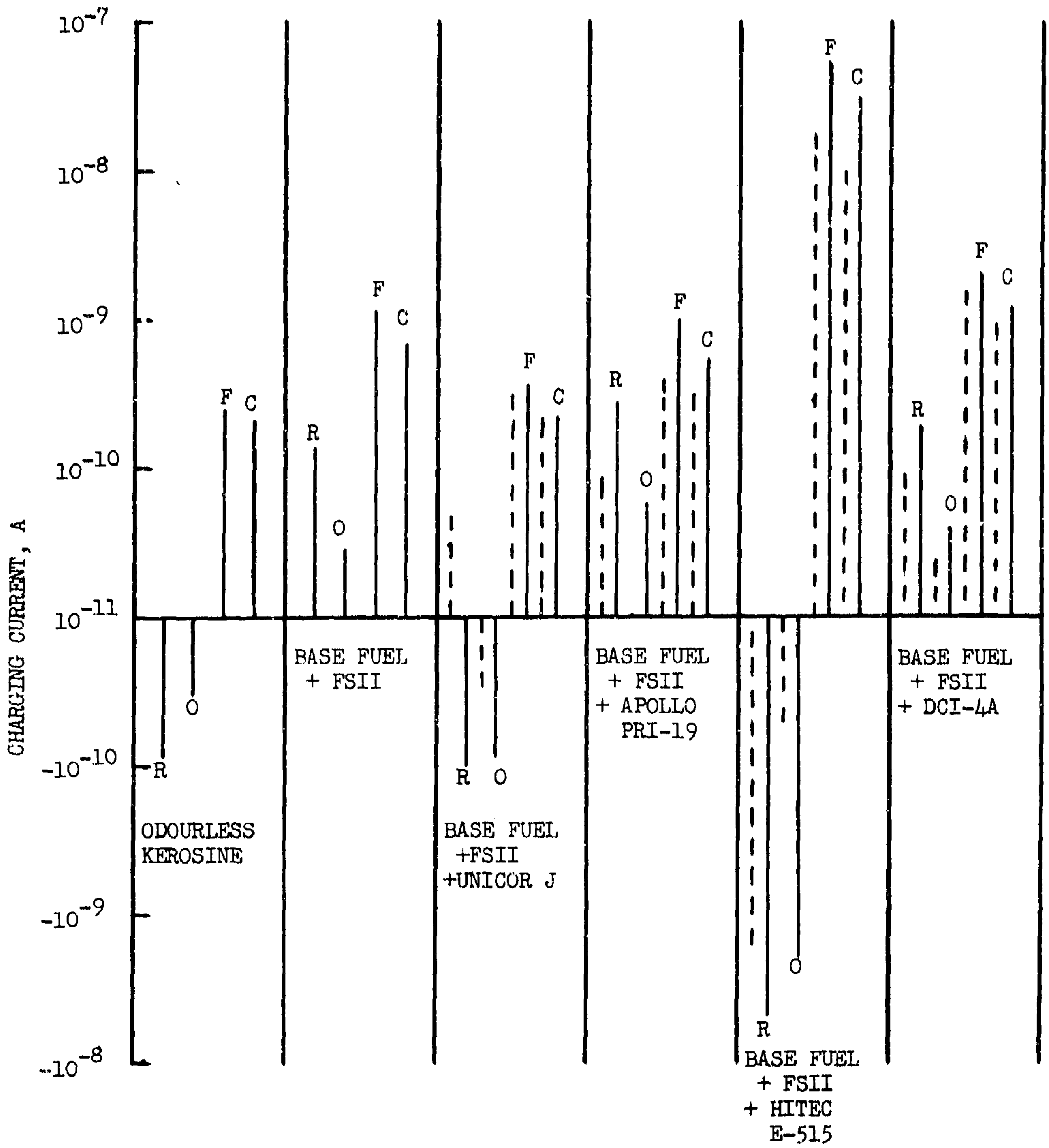


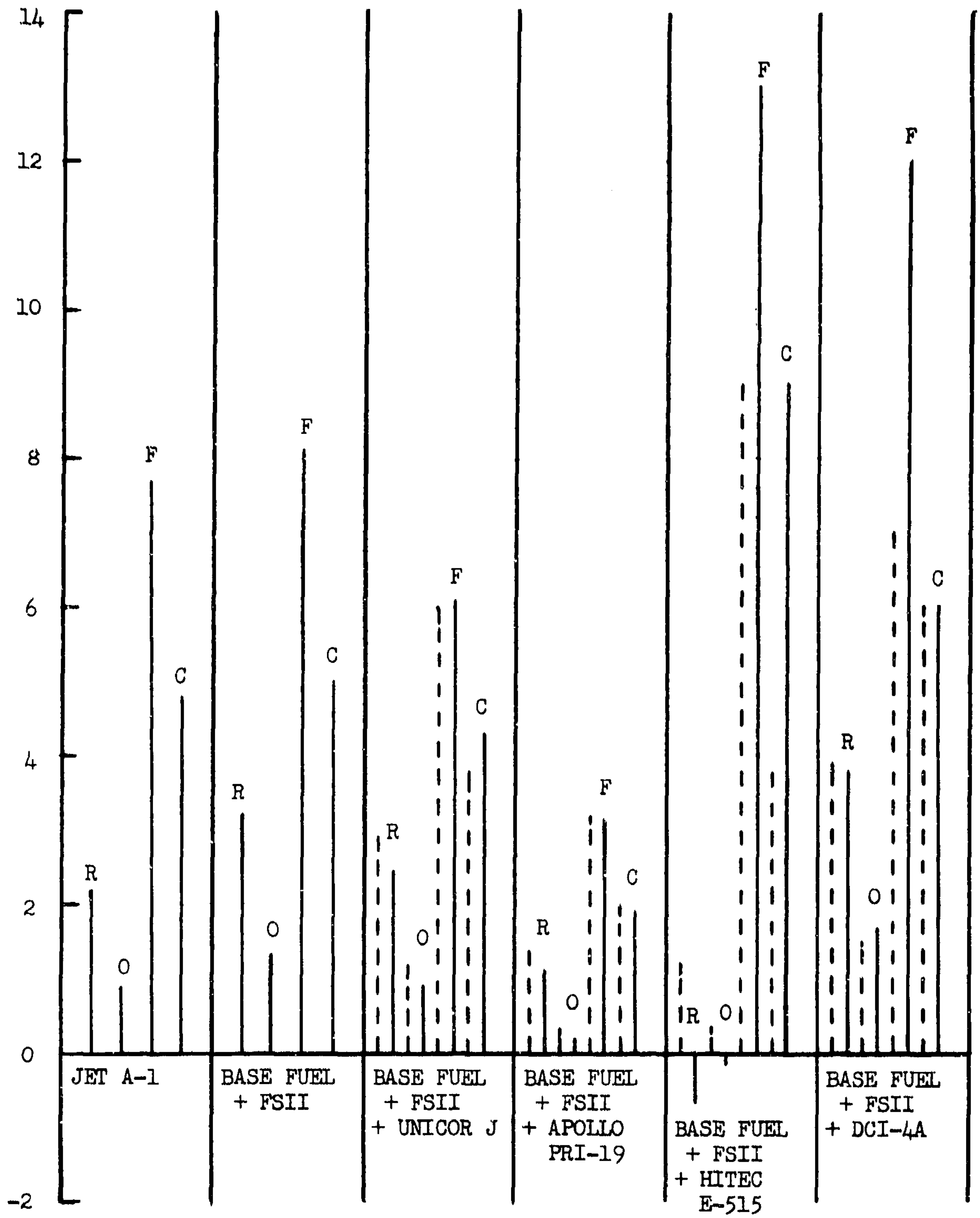
FIG. 2 — Layout inside test tank, showing nozzle positions and void configurations



R = RED POLYESTER FOAM, O = ORANGE POLYESTER FOAM,
F = FINE BLUE POLYETHER FOAM, C = COARSE BLUE POLYETHER FOAM

SOLID LINES REPRESENT MAXIMUM ALLOWED CONCENTRATIONS
BROKEN LINES REPRESENT MINIMUM EFFECTIVE CONCENTRATIONS

FIG. 3 SMALL-SCALE TESTS WITH ODOURLESS KEROSINE



R = RED POLYESTER FOAM, O = ORANGE POLYESTER FOAM,
F = FINE BLUE POLYETHER FOAM, C = COARSE BLUE POLYETHER FOAM

SOLID LINES REPRESENT MAXIMUM ALLOWED CONCENTRATIONS
BROKEN LINES REPRESENT MINIMUM EFFECTIVE CONCENTRATIONS

FIG. 4 SMALL-SCALE TESTS WITH JET A-1

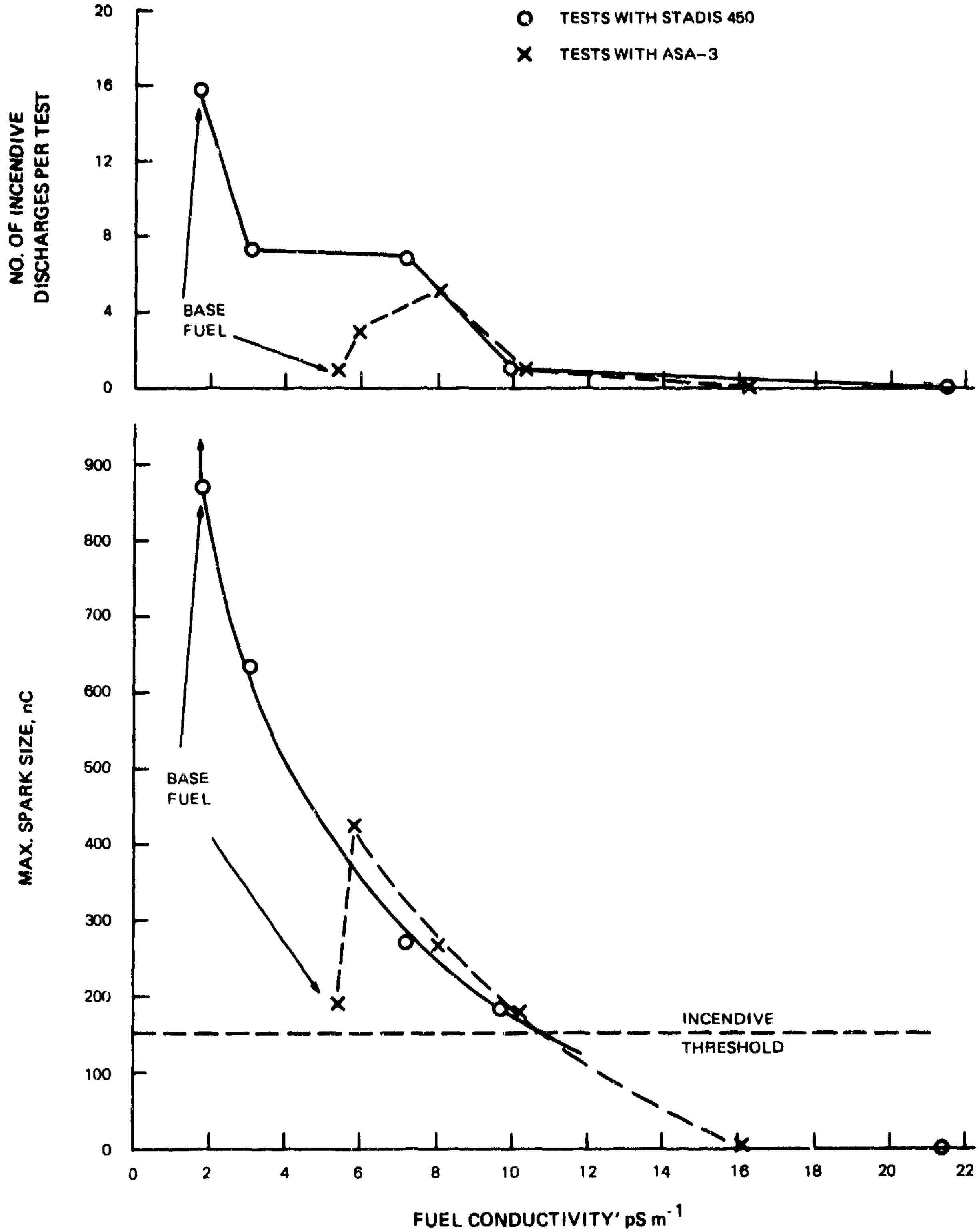


FIG. 5 – Antistatic additive tests with the showerhead nozzle and "clean" base fuel

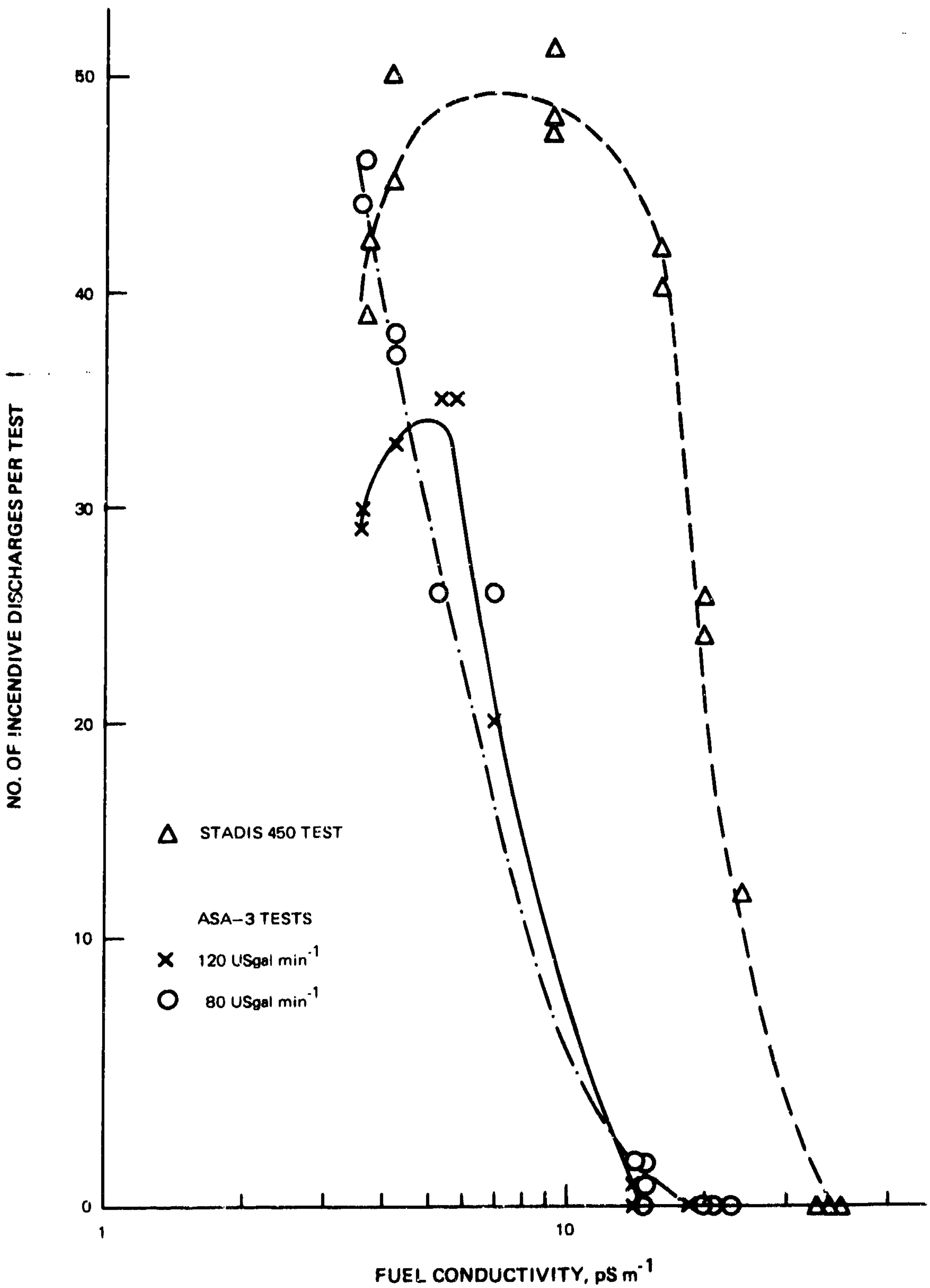


FIG. 6 — Antistatic additive tests with the showerhead nozzle and "hot" fuel

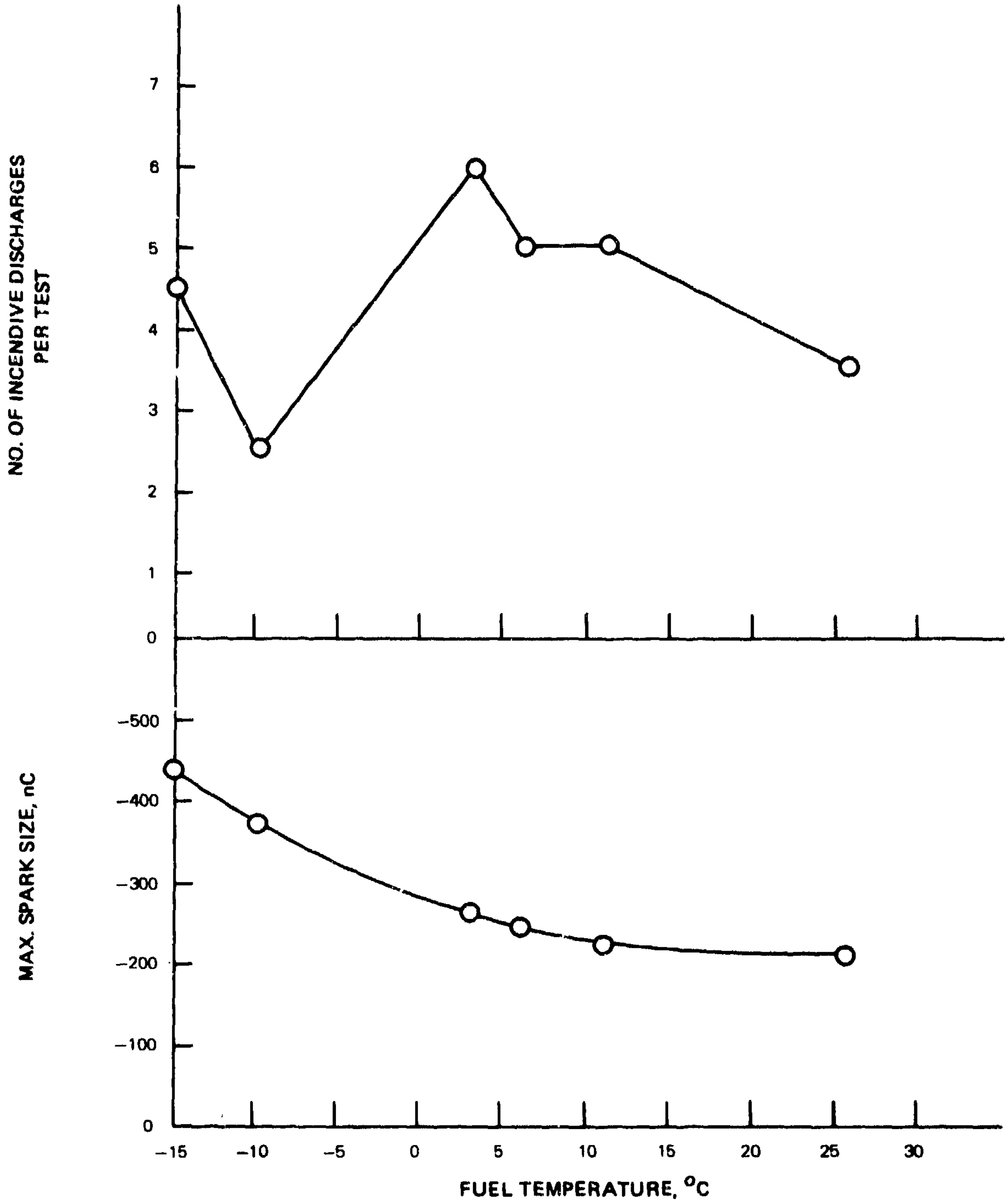


FIG. 7 — Temperature tests with the piccolo inlet and fine blue polyether foam. Fuel: odourless kerosine containing FSII and Hitec E—515.

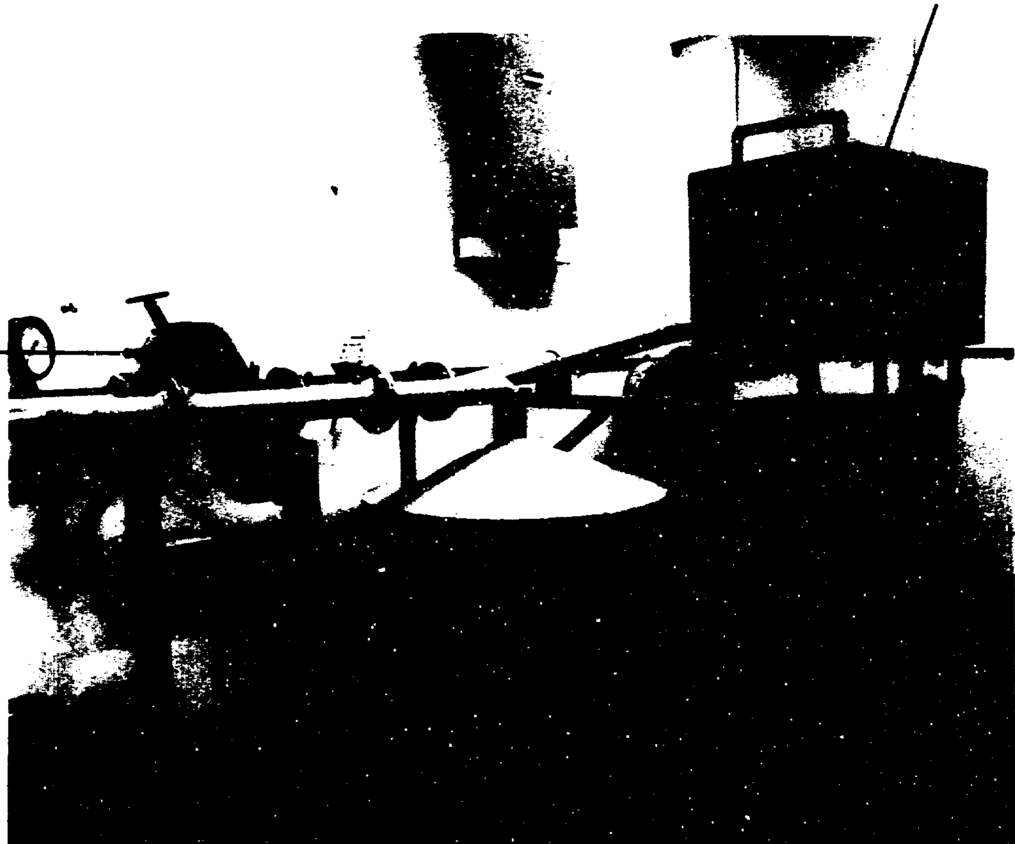


PLATE I — Large-scale tank-filling rig

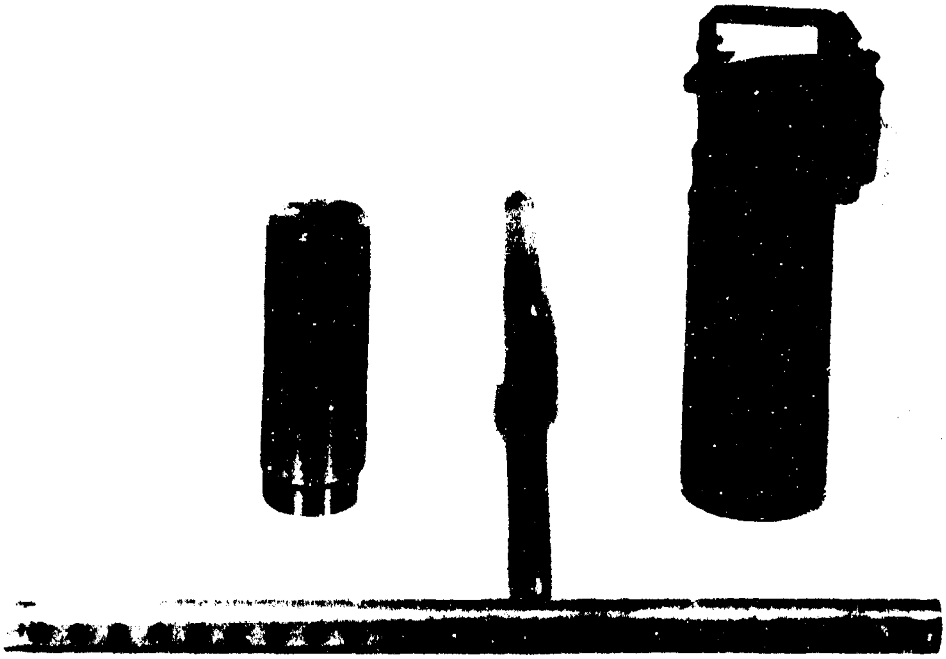


PLATE II — Single-orifice, piccolo and showerhead nozzles

APPENDIX A

Details of small-scale tests

A.1 Foam conductivity measurements

The conductivities of the four types of polyurethane foam and of ICI Promel were measured with the apparatus shown in Figure A1. The foam sample under test was sandwiched between two circular steel plates located inside a Faraday cage. To improve electrical contact a 500-g weight was placed on the top plate. A d.c. voltage was then applied across the plates and the resulting current measured with a Keithley electrometer. The plates had an area of 127 cm^2 and the foam sample a thickness of 10 mm. The conductivity of the foam was given by:

$$\sigma = 7.8 \times 10^{11} \frac{I}{V}$$

where σ = conductivity, pS m^{-1}
I = current, A
V = applied voltage.

In the initial tests with red foam the applied voltage was varied from 0 to 30 V. The conductivity of the foam was found to be constant over this range and therefore all subsequent measurements were made at 30 V. The results are plotted in Figure A2. The error bars reflect the variation inherent in the cutting of samples. It is evident that the conductivities of the polyester urethane foams are an order of magnitude greater than those of the new polyether foams and that ICI Promel has a conductivity similar to that of the polyester foam.

These results are very different from those reported by Dukek et al.[9], who measured foam conductivities by an a.c. method. They recorded conductivities ranging from 1360 pS m^{-1} (fine blue foam) to 8550 pS m^{-1} (red foam) and observed that orange foam had a similar conductivity to that of coarse blue foam. The effective dielectric constant of polyurethane foam should be close to 1, as the polyurethane occupies only 3% of the volume.

Thus the conductivities due to Dukek imply relaxation times in the range 1.2-7.4 ms, whereas the conductivities plotted in Figure A2 give corresponding relaxation times ranging from 0.47 s (orange foam) to 36 s (blue foam). In the tank-filling tests with fine blue foam and clean fuel (conductivity <1 pS m^{-1}), the decay time of the electric field was typically 90 s, i.e. of the same order as the theoretical relaxation time obtained from the d.c. conductivity data and five orders of magnitude longer than the estimate based on the a.c. measurements. The d.c. method is, therefore, more suitable for conductivity measurements of this kind.

A.2 Tests with charging-tendency rig

Each of the corrosion inhibitors specified in the contract was evaluated at the minimum effective and the maximum allowable doping level as given in Section 2.2.5. The test fuel also contained fuel system icing inhibitor (FSII), in each case at a concentration of 0.15%. In order to provide a reference, prior to commencing a test with a particular additive, the charging tendency of the fuel sample used for the test was determined on red polyester foam, before and after addition of icing inhibitor.

A typical data record is shown in Figure A3. The magnitude of the tube current one minute after flow commenced, when equilibrium was attained, was used to quantify the charging tendency of each foam/fuel combination.

The results from the tests with odourless kerosine as the base fuel are given in Tables A1-A6. Several runs were made with each foam at each additive concentration; the values in the Tables are the corresponding averages. It is evident that the activities of the samples of base fuel varied considerably despite their being drawn from the same tank and being clay-treated prior to testing. Although the addition of icing inhibitor generally increased the level of charging on red foam, in the test with Hitec E-515, the effect of this additive was to reduce charging. As the activity of the base fuel will have influenced to an unknown degree the charging tendency after addition of a particular corrosion inhibitor (CI), only the somewhat general conclusions listed in Section 3.1 can be drawn.

The results from the tests with Jet A-1 are given in Tables A7-A12. The conductivities of the samples of base fuel varied from 5.9 to 10 pS m^{-1}, and the corresponding charging currents produced by passing the samples through red foam, before and after the addition of icing inhibitor, varied from +2.1 to +3.1 x 10^{-9} A and +3.1 to +4.1 x 10^{-9} A, respectively; much smaller variations were observed than in the previous tests with odourless kerosine.

In the tests with undoped fuel, all four polyurethane foams charged positively, the charging currents being a factor of 30 greater in magnitude than the corresponding currents recorded in the tests with odourless kerosine. The addition of icing inhibitor to the fuel caused the conductivity to change from 6 to 6.4 pS m^{-1} and increased charging in all cases. The increase was more marked with red and orange foams, being only slight in the case of the blue foams. The addition of Apollo PRI-19 at the minimum effective concentration reduced the conductivity from 6.4 to 4.2 pS m^{-1}. The charging currents from all four foams were also markedly reduced to levels below the values recorded in the tests with undoped fuel. Increasing the additive concentration up to the maximum allowable level did not significantly affect the conductivity or the currents from the polyether foams; however, the currents from the polyester foams were reduced further relative to the tests with clean fuel. These results are quite different from those obtained with odourless kerosine. In the latter case the addition of Apollo PRI-19 resulted in an increase in fuel conductivity together with an increase in charging with all foam types.

Subsequent tests were with new samples of base fuel. The higher activity of the base fuel resulted in the charging currents with the various additives being, in general, considerably greater than in the corresponding tests with odourless kerosine. The addition of Unicor-J caused a reduction in the charging currents from red and orange foams, the reduction being directly related to additive concentration. The blue foams charged to a lesser extent than in the tests with icing inhibitor, even though the results of the two reference tests indicated that the samples of base fuel had similar activities. This finding agrees with the results from the tests with odourless kerosine.

Hitec E-515 reduced the magnitude of the charging currents from red and orange foam, and at the high doping level caused these foams to charge negatively. Conversely, with the blue foams, Hitec E-515 increased charging; a similar result was observed with odourless kerosine. However, the currents from each foam type at both additive concentrations were smaller than the corresponding currents recorded in the tests with odourless kerosine, as were the changes in conductivity resulting from additive addition. These observations suggest that either the degree of dissociation of Hitec E-515 was lower in Jet A-1 or that the ionic mobilities were smaller.

In the tests with DCI-4A all four polyurethane foams charged positively. With one exception (fine blue foam/low additive concentration) the currents recorded were greater than in the corresponding tests with icing inhibitor. The presence of the additive did not affect the conductivity. After completing these tests with polyurethane foam, the sample of fuel containing FSII and DCI-4A (at the maximum allowable concentration) was used to evaluate ICI Promel foam. Four samples of different density were examined and the results are plotted in Figure A4. The error bars reflect the variation inherent in the cutting of samples, which was considerably more difficult than with polyurethane foam as the Promel foam is much less rigid. It is evident that the charging tendency of Promel lies between the charging tendencies of red and coarse blue foams and is weakly dependent on density.

TESTS WITH ODOURLESS KEROSINE

Table A1

Tests with "clean" fuel

Fuel conductivity: 0.5 pS m^{-1} at 23°C

Foam type	Charging current, A
Red	-8.5×10^{-11}
Orange	-3.5×10^{-11}
Blue (fine)	$+2.5 \times 10^{-10}$
Blue (coarse)	$+2.1 \times 10^{-10}$

Table A2

Tests with icing inhibitor

Fuel conductivity: 0.42 pS m^{-1} at 25.5°C

Foam type	Charging current, A
Red	$+1.4 \times 10^{-10}$
Orange	$+3.0 \times 10^{-11}$
Blue (fine)	$+1.2 \times 10^{-9}$
Blue (coarse)	$+7.0 \times 10^{-10}$

Table A3

Tests with Unicor-J

Fuel conductivity: 0.45 pS m^{-1} at 22°C (low CI concentration)
: 0.52 pS m^{-1} at 24°C (high CI concentration)

Foam type	Charging current, A	
Red	$+2.7 \times 10^{-11}$ (clean fuel)	
Red	$+6.5 \times 10^{-11}$ (fuel + FSII)	
	Corrosion inhibitor concentration	
	Minimum	Maximum
Red	$+5.0 \times 10^{-11}$	-1.0×10^{-10}
Orange	-3.1×10^{-11}	-8.3×10^{-11}
Blue (fine)	$+3.3 \times 10^{-10}$	$+3.9 \times 10^{-10}$
Blue (coarse)	$+2.3 \times 10^{-10}$	$+2.3 \times 10^{-10}$

Table A4

Tests with Apollo PRI-19

Fuel conductivity: 0.41 pS m^{-1} at 22°C (low CI concentration)
: 0.77 pS m^{-1} at 24°C (high CI concentration)

Foam type	Charging current, A	
Red Red	$+2.3 \times 10^{-11}$ (clean fuel) $+7.5 \times 10^{-11}$ (fuel + FSII)	
	Corrosion inhibitor concentration	
	Minimum	Maximum
Red	$+9.0 \times 10^{-11}$	$+3.0 \times 10^{-10}$
Orange	$+9.6 \times 10^{-12}$	$+6.0 \times 10^{-11}$
Blue (fine)	$+4.0 \times 10^{-10}$	$+1.0 \times 10^{-9}$
Blue (coarse)	$+3.2 \times 10^{-10}$	$+5.5 \times 10^{-10}$

Table A5

Tests with Hitec E-515

Fuel conductivity: 3.4 pS m^{-1} at 25°C (low CI concentration)
: 6.8 pS m^{-1} at 24°C (high CI concentration)

Foam type	Charging current, A	
Red Red	-8.5×10^{-11} (clean fuel) $+1.4 \times 10^{-10}$ (fuel + FSII)	
	Corrosion inhibitor concentration	
	Minimum	Maximum
Red	-1.6×10^{-9}	-4.8×10^{-9}
Orange	-0.5×10^{-10}	-2.1×10^{-9}
Blue (fine)	$+1.8 \times 10^{-8}$	$+6.0 \times 10^{-8}$
Blue (coarse)	$+1.0 \times 10^{-8}$	$+3.1 \times 10^{-8}$

Table A6

Tests with DCI-4A

Fuel conductivity: 0.45 pS m^{-1} at 24°C (low CI concentration)
: 0.69 pS m^{-1} at 26°C (high CI concentration)

Foam type	Charging current, A	
Red Red	$+10^{-10}$ (clean fuel) $+1.4 \times 10^{-11}$ (fuel + FSII)	
	Corrosion inhibitor concentration	
	Minimum	Maximum
Red Orange Blue (fine) Blue (coarse)	$+9.0 \times 10^{-11}$ $+2.2 \times 10^{-11}$ $+1.6 \times 10^{-9}$ $+9.0 \times 10^{-10}$	$+2.1 \times 10^{-10}$ $+4.0 \times 10^{-11}$ $+2.0 \times 10^{-9}$ $+1.2 \times 10^{-9}$

TESTS WITH JET A-1

Table A7

Tests with "clean" fuel

Fuel conductivity: 5.9 pS m^{-1} at 16°C

Foam type	Charging current, A
Red	$+2.1 \times 10^{-9}$
Orange	$+8.4 \times 10^{-10}$
Blue (fine)	$+7.7 \times 10^{-9}$
Blue (coarse)	$+4.8 \times 10^{-9}$

Table A8

Tests with icing inhibitor

Fuel conductivity : 6.4 pS m^{-1} at 19°C

Foam type	Charging current, A
Red	$+3.2 \times 10^{-9}$
Orange	$+1.3 \times 10^{-9}$
Blue (fine)	$+8.1 \times 10^{-9}$
Blue (coarse)	$+5.0 \times 10^{-9}$

Table A9

Tests with Unicor - J

Fuel conductivity: 5.4 pS m^{-1} at 20°C (low CI concentration)
: 6.9 pS m^{-1} at 21°C (high CI concentration)

Foam type	Charging current, A	
Red Red	$+2.3 \times 10^{-9}$ (clean fuel) $+3.2 \times 10^{-9}$ (fuel + FSII)	
	Corrosion inhibitor concentration	
	Minimum	Maximum
Red	$+2.9 \times 10^{-9}$	$+2.4 \times 10^{-9}$
Orange	$+1.2 \times 10^{-9}$	$+9.1 \times 10^{-10}$
Blue (fine)	$+6.0 \times 10^{-9}$	$+6.1 \times 10^{-9}$
Blue (coarse)	$+3.8 \times 10^{-9}$	$+4.3 \times 10^{-9}$

Table A10

Tests with Apollo PRI-19

Fuel conductivity: 4.2 pS m^{-1} at 22°C (low CI concentration)
: 4.1 pS m^{-1} at 24°C (high CI concentration)

Foam type	Charging current, A	
Red Red	$+2.1 \times 10^{-9}$ (clean fuel) $+3.2 \times 10^{-9}$ (fuel + FSII)	
	Corrosion inhibitor concentration	
	Minimum	Maximum
Red	$+1.4 \times 10^{-9}$	$+1.1 \times 10^{-9}$
Orange	$+3.7 \times 10^{-10}$	$+2.0 \times 10^{-10}$
Blue (fine)	$+3.2 \times 10^{-9}$	$+3.2 \times 10^{-9}$
Blue (coarse)	$+2.0 \times 10^{-9}$	$+1.9 \times 10^{-9}$

Table A11

Tests with Hitec E-515

Fuel conductivity: 10 pS m^{-1} at 21°C (low CI concentration)
: 12 pS m^{-1} at 25°C (high CI concentration)

Foam type	Charging current, A	
Red Red	$+2.5 \times 10^{-9}$ (clean fuel) $+3.2 \times 10^{-9}$ (fuel + FSII)	
	Corrosion inhibitor concentration	
	Minimum	Maximum
Red	$+1.2 \times 10^{-9}$	-5.0×10^{-10}
Orange	$+3.4 \times 10^{-10}$	-1.8×10^{-10}
Blue (fine)	$+9.0 \times 10^{-9}$	$+1.3 \times 10^{-8}$
Blue (coarse)	$+3.8 \times 10^{-9}$	$+9.0 \times 10^{-9}$

Table A12

Tests with DCI-4A

Fuel conductivity: 10 pS m^{-1} at 22°C (low CI concentration)
: 10 pS m^{-1} at 24°C (high CI concentration)

Foam type	Charging current, A	
Red Red	$+3.1 \times 10^{-9}$ (clean fuel) $+4.1 \times 10^{-9}$ (fuel + FSII)	
	Corrosion inhibitor concentration	
	Minimum	Maximum
Red	$+3.9 \times 10^{-9}$	$+3.8 \times 10^{-9}$
Orange	$+1.5 \times 10^{-9}$	$+1.7 \times 10^{-9}$
Blue (fine)	$+7.0 \times 10^{-9}$	$+1.2 \times 10^{-8}$
Blue (coarse)	$+6.0 \times 10^{-9}$	$+6.0 \times 10^{-9}$

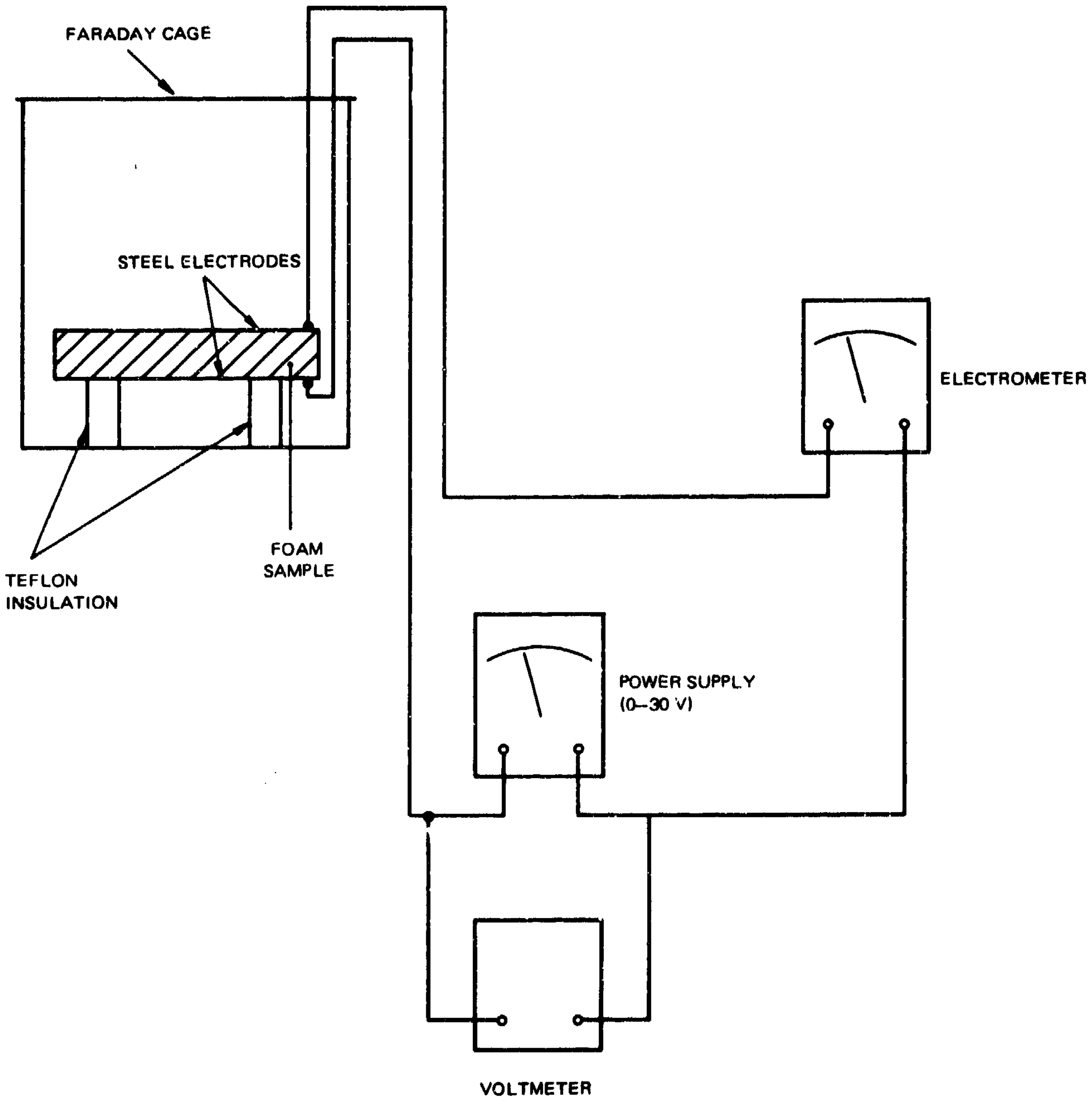


FIG. A1 — Conductivity measuring apparatus

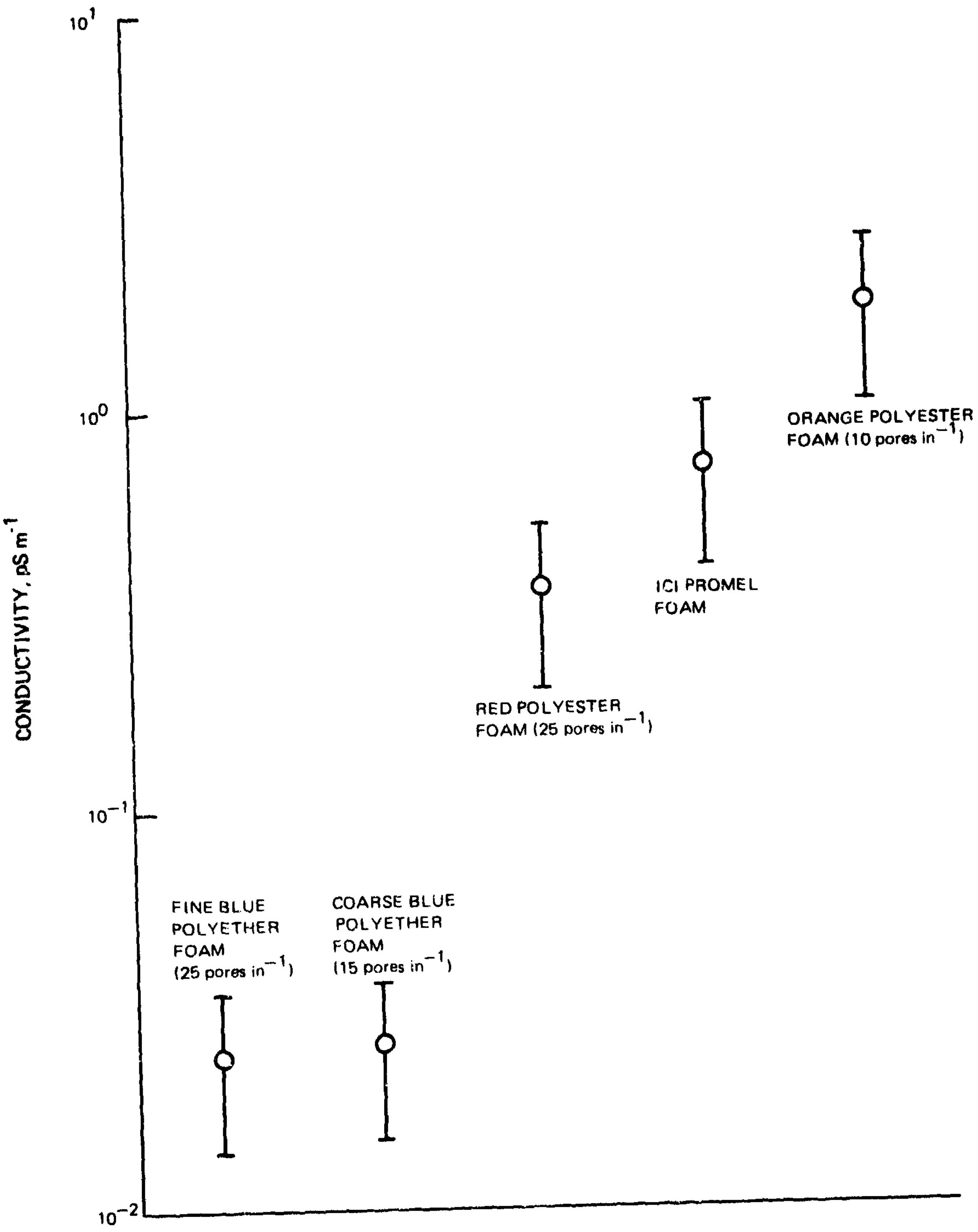


FIG. A2 – Foam conductivities

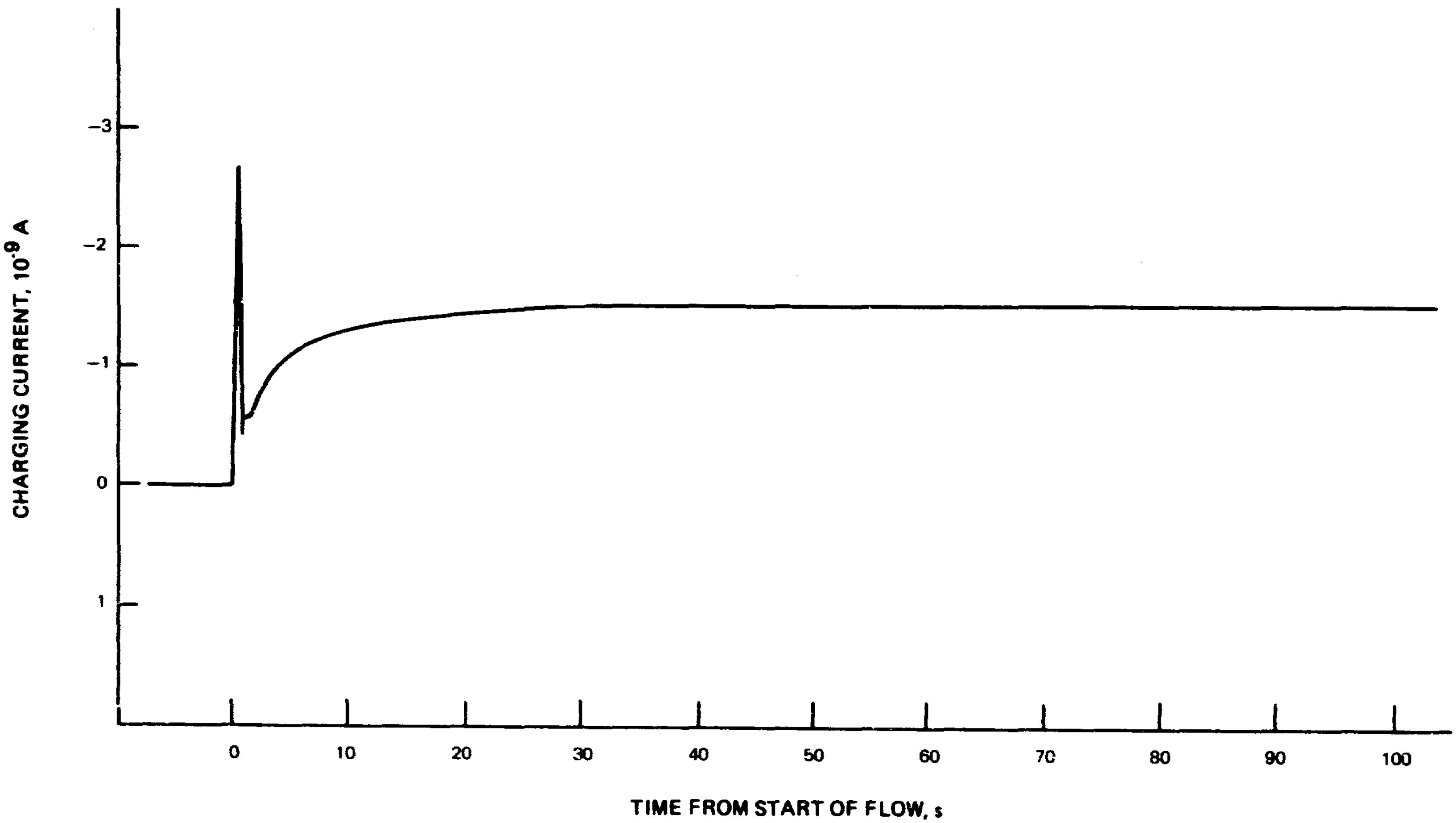


FIG. A3 — Charging tendency of Hitec E–515 on red polyester foam

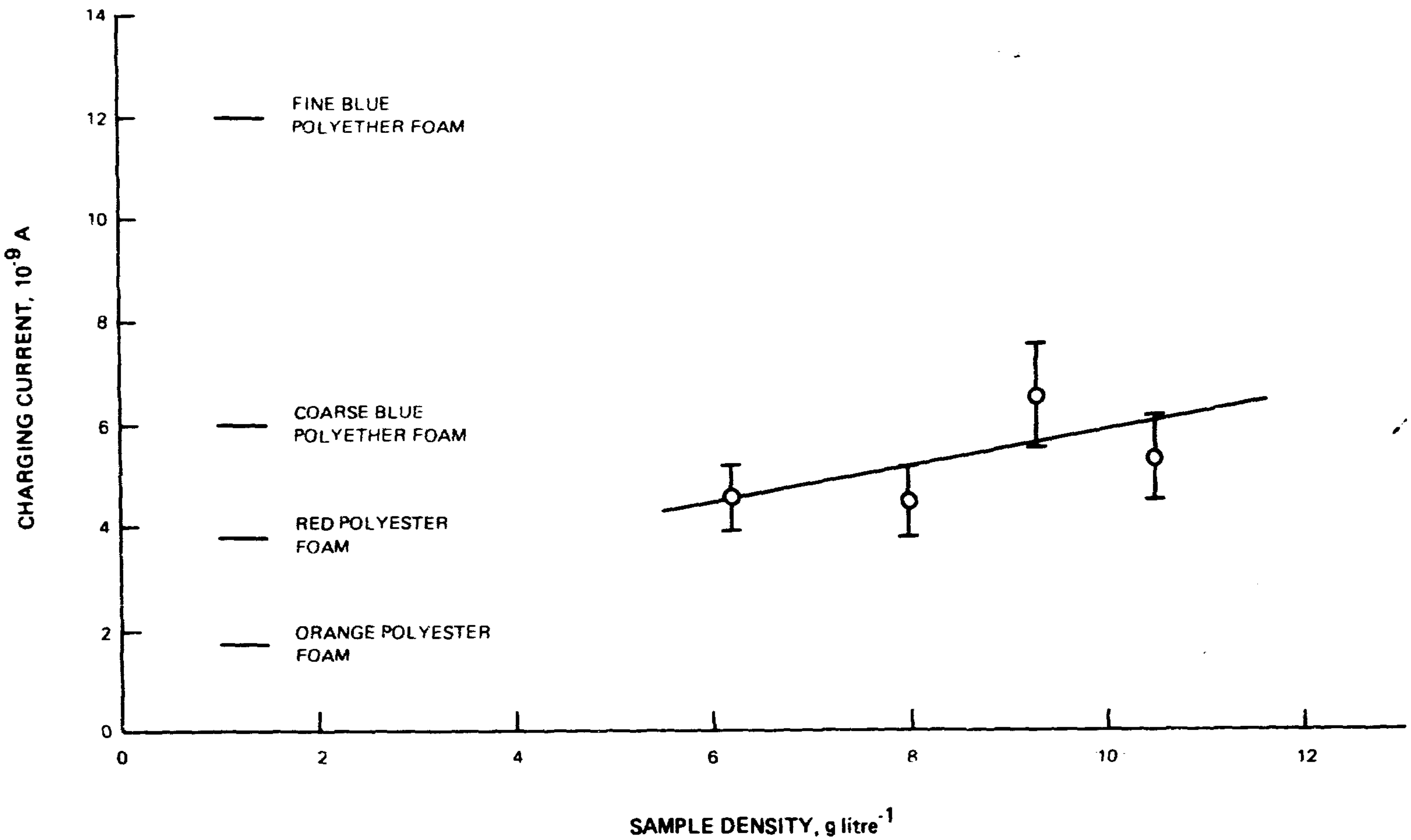


FIG. A4 — Charging tendency of ICI Promel foam

APPENDIX B

Details of tank-filling tests

B.1 Measuring techniques

To measure the magnitudes of sparks occurring to the inlet nozzle during a filling test, the nozzle was electrically isolated from the rest of the system and connected in series with a capacitor, the other side of which was connected to ground. As shown in Figure B1 the voltage rise across the capacitor produced by a discharge, from which the total charge transferred could be determined, was measured with a Gould 4100 storage oscilloscope that enabled a complete data record of sparking during a test to be obtained.

In the tests with the single-orifice and showerhead nozzles and clean fuel, the use of the storage oscilloscope also allowed measurement of the current induced to the nozzle by the electric field created by the charged foam, the peak of this current being directly related to the rate of charge generation in the foam. To understand how this applies, consider the arrangement with the single orifice inlet as shown in Figure B1. During tank filling, fuel with a high discharge velocity impinges on the region of foam opposite the nozzle, disperses through the foam and finally sinks into the tank, leaving the foam with a net charge. This charge produces an electric field at the inlet nozzle and hence charge is induced to flow to the nozzle from ground.

The region of foam opposite the nozzle can be visualised as one plate of a leaky capacitor onto which a constant charging current, I, is being fed. I is equal to the rate of charge generation and will be a function of the nozzle type, foam type, flow rate, inlet velocity and fuel type.

Let C_N = capacitance between foam and nozzle, and

C_S = capacitance between foam and surroundings excluding nozzle.

To a first approximation, these capacitances will be constant for a particular type of nozzle and void configuration.

Then, referring to Figure B2:

$$I = I_N + I_S + I_R$$

At time t, let the charge on $C_N = Q_N(t)$, and

the charge on $C_S = Q_S(t)$.

Substituting:

$$I = \frac{dQ_N}{dt} + \frac{dQ_S}{dt} + \frac{Q_N}{RC_N} \qquad \text{..... (1)}$$

R is the electrical resistance between the charged foam and earth and will be a function of the conductivities of the foam and fuel.

Substituting $Q_S = \frac{C_S}{C_N} QN$ in (1) and rearranging:

$$\frac{dQ_N}{IRC_N - Q_N} = \frac{dt}{R(C_N + C_S)}$$

Thus:

$$\int_0^t \frac{dQ_N}{IRC_N - Q_N} = \int_0^t \frac{dt}{R(C_N + C_S)}$$

Which gives $Q_N = IRC_N - Ae^{-t/R(C_N+C_S)}$, where A = constant

At $t = 0$, $Q_N = 0$ and therefore $A = IRC_N$

$$\therefore \quad \underline{Q_N = IRC_N \left(1 - e^{-t/R(C_N+C_S)}\right)} \qquad \text{..... (2)}$$

The current measured on the oscilloscope will be given by:

$$I_N = \frac{dQ_N}{dt} = \frac{IC_N\ e^{-t/R(C_N+C_S)}}{C_N + C_S} \qquad \ldots\ldots (3)$$

i.e. a decaying exponential that has its maximum value at t = 0, this maximum being directly proportional to the rate of charge generation, I. Figure B3 shows a typical nozzle signal, recorded during a test with the single-orifice inlet and red foam. The negative spike at the start of the test was caused by negatively charged fuel, charge density approximately $-3\ \mu C\ m^{-3}$, entering the nozzle. The peak in the signal when flow commenced is clearly visible, and the fact that the signal did not attain a maximum value immediately the fuel entered the foam arose from the initial quantity of fuel taking a finite time to sink through the foam into the tank.

Estimating the rate of charge generation by this method could be used only in the initial tests with clean fuel. In subsequent tests with more active fuel and different void configurations, currents to the nozzle from other sources, in particular from the charged fuel, made it impossible to distinguish the initial induction peak. In these tests the number and magnitude of sparks to the nozzle was used to quantify the hazard presented.

B.2 Tests with "clean" fuel

The single-orifice and showerhead nozzles were evaluated with red and coarse blue foam, using a test fuel of clay-treated odourless kerosine. The effect on charging by varying the discharge velocity and the filling rate was determined.

Figures B3 and B4 show typical nozzle and fieldmeter signals produced during tests with the single-orifice inlet and red and blue foam, respectively. In the tests with red foam, the electric field peaked shortly after filling commenced and then gradually decayed. In the tests with blue foam the field plateaued, rather than peaked, at a value that was typically a factor of 15 greater than the peak in the corresponding tests with red foam. Only after filling ceased did the field begin to decay. These differences between the behaviour of red and blue foam result from the latter having a much lower conductivity. However, the nozzle signals recorded with the two foam types had very similar decay times, (the decays being only pseudo exponential). This is rather surprising because formula (3) in Appendix B.1 indicates that the decay should be exponential, with a time constant inversely proportional to the conductivity of the foam. The reason why this was not the case could be related to the fact that in the tests with blue foam, the nozzle was enveloped in charged foaming fuel for much of the test, which was not the case with red foam, and this could have resulted in the nozzle being partially screened from the electric field produced by the charged foam.

The results from the various tests with the single-orifice inlet are given in Tables B1 and B2 and plotted in Figures B5 and B6. Each value of peak nozzle current and electric field maximum represents the average of several readings. As mentioned in Section 3.2.1, the fuel appeared to absorb a pro-charging substance from the blue foam, which resulted in the occurrence of potentially incendive discharges during tests to evaluate the effect of varying the filling rate. The fuel was therefore clay-treated before proceeding, and sparking was not observed in subsequent tests with this inlet and fuel. In the tests to evaluate the dependence of charging on inlet velocity, the electric field readings indicated that the rate of charge generation increased with discharge velocity for both foam types. However, the peak nozzle currents were found to be inversely related to discharge velocity, the effect being more marked with blue foam. This was possibly owing to the region of charge separation moving away from the nozzle, hence reducing the value of C_N (the foam-to-nozzle capacitance), as a result of the increased fuel velocity, the variation being greater with the blue foam because of the more open structure of this material. In the tests to evaluate the effect of filling rate, both the peak current and maximum field readings showed that the rate of charge generation increased with filling rate with both foam types. In the tests with blue foam it was not possible to obtain a reading of the initial current peak in the tests made at a filling rate of 120 USgal min^{-1}, owing to the induced current being swamped by that from the charged fuel, which completely enveloped the nozzle immediately after filling commenced.

Figure B7 shows the experimental arrangement for the tests with the showerhead nozzle; the results from the tests with coarse blue and red foam are given in Tables B3 and B4, respectively. The fieldmeter readings are not given as they were very low, being typically <2 kV m^{-1}, which was caused primarily by the close proximity of the meter to the earthed nozzle. In the first two runs with blue foam, there was much evidence of sparking on the combined inlet pipe and nozzle signal. When the signals from these components were examined separately, it was found that sparking occurred to the inlet pipe only and that the peak nozzle induction current was an order of magnitude lower than the peak inlet pipe induction current. The signals were therefore combined for the remainder of the tests. It was postulated that sparking might be a result of fuel contamination, and the kerosine was therefore clay-treated until its conductivity was reduced from 1.1 to 0.46 pS m^{-1}. Although in the first instance this actually resulted in an increase in the amount of sparking, the activity of the fuel gradually decreased with time, and sparking was completely absent in later tests. This could have arisen as a result of the removal of some component from the fuel. All the discharges observed had magnitudes well below the incendive threshold of +150 nC. It was evident that the peak nozzle current at a particular flow rate was generally inversely related to the sparking activity, i.e. the presence of sparks caused a reduced nozzle current. In view of this it was assumed that the peak nozzle current was only a measure of the rate of charge generation during filling tests where sparking did not occur. The results from these tests are plotted in Figure B8; the straight line corresponds to a least squares fit. Although there is a large amount of scatter in the data, the increase in charge generation with filling rate can be clearly seen. The results from the tests with red foam are plotted in Figure B9; again the rate of charge generation increased with filling rate.

In the tests with both the showerhead and single-orifice inlets, the peak nozzle current was, on average, a factor of 6 greater in the tests with coarse blue foam than in the tests with red foam, indicating that the former generates charge at a rate 6 times that of the latter under identical test conditions. This is in good agreement with the results from the small-scale tests with odourless kerosine. The peak currents in the showerhead tests were an order of magnitude greater than those in the corresponding single-orifice tests, primarily as a result of the different geometrical configurations.

B.3 Tests with fuel comprising odourless kerosine containing FSII and Hitec E-515 (Results in Tables B5-B7)

To simulate the case of a "real" fuel, FSII and Hitec E-515 were added to the odourless kerosine used in the previous tests, the former at a concentration of 0.15% and the latter at the minimum effective concentration (21.4 mg $litre^{-1}$). The three nozzles were then evaluated with fine blue foam. The single-orifice inlet was repositioned at the bottom of the tank and the effect of directing fuel both into the foam and against the tank wall was determined (see Figure 2).

In these, and in all subsequent tests, the foam charged positively and the fuel negatively. Sparking was only observed in the tests with the piccolo inlet and normally started about 30 seconds after filling commenced. The sparks occurred between the fuel and the vertical stem of the piccolo tube and were therefore of negative polarity. Spark magnitudes increased with filling rate, but at the maximum rate attainable (90 USgal min^{-1}) they were still below the incendive threshold for negative discharges (-75 nC).

B.4 Antistatic additive doping tests with "clean" base fuel

Apart from one test with the showerhead nozzle where Promel foam was evaluated, fine blue foam was used for all this work. Results obtained using single orifice, showerhead and piccolo inlets are given in Tables B8-B13.

B.4.1 Single-orifice inlet (Results in Table B8)

The tests with ASA-3 were carried out under two sets of filling conditions: high filling rate/average inlet velocity (120 USgal min^{-1} and 40 ft s^{-1}) and nominal filling rate/high inlet velocity (72 USgal min^{-1} and 58 ft s^{-1}). The effect of discharging fuel into the foam and against the tank wall was determined in each case. In the first series of tests, ASA-3 was progressively added to the fuel. In the second series the conductivity of the fuel was gradually reduced by clay treatment. In both cases, sparking was only observed when fuel was directed into the foam, the discharges producing charge transfers to the nozzle of both positive and negative polarity. It was later realised that these discharges were not simply between the foam and the nozzle, but from the foam to its surroundings, which of course included the nozzle. Thus estimating the magnitudes of discharges from the corresponding nozzle signals, as given in Table B8, provided only lower limits on their actual size. In view of this the only conclusions that can be drawn from the results of these tests is that fuels with a high discharge velocity should not be directed into foam. Where this was the case, sparking still occurred at a conductivity of 80 pS m^{-1}.

B.4.2 Showerhead inlet (Results in Tables B9, B12, B13)

The tests with ASA-3 were made at two filling rates, 120 and 80 USgal min^{-1}, and the magnitude and frequency of sparks determined as the conductivity of the fuel was first increased and then reduced by clay treatment. Frequent sparking was observed at conductivities below 10 pS m^{-1}. In these tests, sparking to the inlet pipe began shortly after filling commenced, the sparks being small and of both positive and negative polarity. When the tank was half full, sparks of incendive magnitude occurred to both the nozzle shroud and the inlet pipe, the sparks being from the walls of the void and hence of positive polarity, except for one instance (test no. B107) where a large negative spark was detected. During the latter half of the test the nozzle was enveloped in foaming fuel, which collapsed when the flow was terminated. At this instant, extensive sparking between the walls of the void and the nozzle occurred, the discharges having magnitudes <+30 nC. It was evident from the data that at a particular conductivity, fewer discharges were observed in the tests where ASA-3 was being progressively added than in tests where the conductivity was being gradually reduced by clay treatment. This indicates that clay treatment did not remove the components of the additive uniformly and that results from the two test series cannot be compared directly. Thus the practice of taking measurements as the conductivity was reduced was discontinued. Only results from those tests where the conductivity was gradually increased have been plotted in Figure 5. A conductivity of 16 pS m^{-1} was sufficient to suppress all sparking.

In the Stadis 450/fine blue foam test, frequent sparking was observed with the base fuel before the addition of Stadis 450, the number and peak magnitude of the sparks thereafter decreasing with progressive doses of the additive. As with ASA-3, the results indicated that a conductivity of about 16 pS m^{-1} was sufficient to stop all sparking.

In the tests with Promel, discharges were detected in only two runs, rather surprisingly at a high fuel conductivity (22-31 pS m^{-1}). However, the discharges were very small and were well below the incendive threshold. These results confirm those from the small-scale tests on the relative hazards presented by fine blue foam and Promel.

B.4.3 Piccolo inlet (Results in Tables B10 and B11)

These tests were all made at a filling rate of 90 USgal min^{-1}, and discharges between the charged fuel and the vertical stem of the nozzle were observed with both ASA-3 and Stadis 450. The magnitude of the largest spark observed during each test run is plotted in Figure B10 as a function of fuel conductivity. Although there is a large amount of scatter in the data, it is evident that none of the sparks were potentially incendive and that conductivities of 19 and 8 pS m^{-1} stopped all sparking in the Stadis 450 and ASA-3 tests, respectively.

B.5 Antistatic additive doping tests with "hot" fuel

B.5.1 Pro-charging additive

In the earlier work[4] at Thornton Research Centre on polyurethane foam, 1-decene polysulphone was added to the test fuel (odourless kerosine) to increase its electrostatic activity. In the foam work carried out by Exxon[9], Gulf Additive 178, a corrosion inhibitor, was used as a pro-charging agent, the base fuel being Jet A-1. In order to determine the most suitable pro-charger to use in this present work, both additives were evaluated on the small-scale charging-tendency rig, using red and fine blue foams. The fuel samples used in the two tests had similar initial conductivities and activities.

The results are plotted in Figures B11 and B12. The Gulf additive, GA-178, caused red foam to charge negatively when present at a concentration above 1 ppm (w/v), the magnitude of the charging current thereafter increasing linearly with additive concentration. Over the range of concentrations examined, the additive actually reduced the magnitude of the charging current from the sample of blue foam and increased the conductivity of the fuel from 1.5 pS m^{-1} (clean fuel) to 3.7 pS m^{-1} at a concentration of 4 ppm.

The charging tendency of 1-decene polysulphone was found to be strikingly different. Both foams charged positively and the charging currents were found to be directly proportional to additive concentration. At a concentration of only 0.1 ppm (fuel conductivity 5.8 pS m^{-1}) the current from blue foam was two orders of magnitude greater than that observed in the corresponding tests with GA-178. In view of this it was decided to use the polysulphone as the pro-charging additive in the tank filling tests.

B.5.2 Showerhead inlet (Results in Tables B14 and B15)

These tests were initially carried out with progressive addition of ASA-3 to active fuel and then repeated with Stadis 450. The results are plotted in Figure 6.

The ASA-3 tests were made at two filling rates, 80 and 120 USgal min^{-1}. Starting with clean fuel (conductivity <1 pS m^{-1}), polysulphone was added until the fuel's activity was significantly greater than that of the base fuel in the showerhead/antistatic additive tests with clean fuel. A total of 0.077 ppm of 1-decene polysulphone was added and, at this concentration, 30-35 potentially incendive discharges were observed during each test. Most of the discharges were of positive polarity and had much greater magnitudes (up to +1500 nC) than the occasional negative sparks that were detected. The first addition of ASA-3 (0.01 ppm) actually reduced the conductivity of the fuel from 5.9 to 3.4 pS m^{-1} and increased the number of incendive discharges. A total of 0.11 ppm of ASA-3 had to be added to raise the conductivity of the fuel to its former level. Thereafter, additions of ASA-3 reduced the activity of the fuel, and a conductivity of 20 pS m^{-1} suppressed all sparking, although the curves in Figure 6 suggest that a conductivity of 17 pS m^{-1} would have been sufficient to prevent discharges occurring at both filling rates. The reduction in conductivity when ASA-3 was first added could have been a result of an interaction between the additive and the polysulphone.

The Stadis 450 tests were all made at a filling rate of 80 USgal min^{-1}, noting that this filling rate gave the more critical case in the ASA-3 tests. After cleaning the fuel, polysulphone was added until at a conductivity of 3.7 pS m^{-1}, the fuel had a similar activity to that in the previous tests at this conductivity level. There was no drop in conductivity when Stadis 450 was first added. A conductivity of 37 pS m^{-1} was required to suppress all sparking and thus, in terms of conductivity, ASA-3 was more efficient at reducing the hazard presented by the system.

B.5.3 Single-orifice inlet (Results in Table B16)

The tests were made at a filling rate of 72 USgal min^{-1} and an inlet velocity of 58 ft s^{-1}. Fuel was directed either against the tank wall or into a block of foam placed in front of the nozzle.

Starting with clean fuel, polysulphone was added until many large discharges occurred during a test. For test number B219, a section of foam was removed from the tank to facilitate observation of the discharges with the low-light-level camera system. It was discovered that the bright roots of the discharges were located on the surface of the foam block into which the fuel was directed, and not on the nozzle as with the other inlets examined. Thirty-two of the larger sparks corresponded to charge transfers to the nozzle in excess of +150 nC and appeared as very diff ıe flashes centred on the foam block. In addition to these phenomena, 18 large discharges of a different nature were observed. These consisted of a bright root which split into several less luminous channels that tracked to the base of the tank or back towards the adjacent wall. These discharges produced negative-going pulses on the nozzle trace. It was realised that the magnitudes of the pulses recorded from the nozzle provided only lower limits to the sizes of the discharges that produced them.

Progressive additions of ASA-3 to the fuel increased its conductivity and reduced the number of large discharges. Between runs B228 and B229 the system was left to stand overnight, after which the conductivity was found to have risen from 15 to 39 pS m^{-1}. At this conductivity, sparking was not observed when fuel was directed against the tank wall. The apparently delayed response of ASA-3 could have arisen from the presence of polysulphone in the fuel. However, sparking still occurred when the fuel was directed into the foam block. At a conductivity of 155 pS m^{-1} and above, these discharges were confined to a short period after filling commenced and were probably non-incendive; however, they were still visible with the camera system. At a conductivity of 190 pS m^{-1}, reducing the inlet velocity from 58 to 9 ft s^{-1} did not eliminate these discharges. These results demonstrate further the importance of not directing fuel into foam.

B.5.4 <u>Piccolo inlet</u> (Results in Table B17)

These tests were all made at a filling rate of 90 USgal min^{-1}. Although some incendive discharges between the charged fuel and the vertical stem of the inlet were detected after the first addition of polysulphone, after several tests sparking ceased and could not be made to occur again even though the fuel was made highly active by further additions of pro-charger. The tests were therefore terminated.

B.6 Low-temperature tests and tests to determine the effect of free water

These tests were all carried out with the piccolo inlet and fine blue foams and at a filling rate of 90 USgal min^{-1}.

B.6.1 Low-temperature tests (Results in Tables B18 and B19)

For these tests the tank-filling rig was moved into a "cold room". The system was refilled with a new batch of odourless kerosine and the simulated aircraft tank repacked with a new sample of fine blue foam.

For the first series of tests, FSII (0.15%v) and Hitec E-515 (at the minimum effective level) were added to the odourless kerosine. Contrary to the earlier work with this fuel (see Appendix B.3), incendive discharges were observed in the tests at ambient temperature. This could have been a result of using new foam. However, as shown in Figure 7, reducing the temperature of the fuel to -15°C did not increase the number of such discharges per test, although an increase in the magnitude of the sparks was recorded. The conductivity of the fuel decreased as the temperature of the fuel was reduced, going from 5.0 pS m^{-1} at 20°C to 0.9 pS m^{-1} at -15°C. After several tests at -15°C, the fuel was allowed to warm up slowly over a period of several days. When further tests were carried out at temperatures between 14.0 and 19.0°C, it was discovered that incendive discharges between the fuel and the nozzle no longer occurred. Furthermore, the conductivity of the fuel was found to have been reduced relative to the conductivity in the earlier tests at ambient temperature. This indicates that some component had been removed from the fuel, either as a result of pumping the fuel through the rig or by thermal cycling the system.

For the second series of tests, the fuel, which still contained FSII and Hitec E-515, was made electrostatically "hot" by the addition of polysulphone. Again contrary to the earlier work, incendive discharges were observed in the tests at ambient temperature. ASA-3 was then added to the fuel, and a conductivity of 18 pS m^{-1} was sufficient to suppress all sparking. The temperature of the fuel was then gradually reduced to -15°C. Lowering the temperature did not result in the re-appearance of sparking. One interesting feature of these tests was the effectiveness of ASA-3 at increasing the conductivity of the fuel, only 0.02 ppm being required to put the conductivity up from 11 to 18.5 pS m^{-1}. This was almost certainly caused by an interaction between the additive and the Hitec E-515 present in fuel, the latter being known to boost the activity of ASA-3.

Summarising, the results from the limited number of tests carried out indicates that reducing the temperature of the fuel to values at least as low as -15°C does not give significantly increased hazard.

B.6.2 Tests with free water (Results in Table B20)

In order to carry out these tests, the fuel from the temperature tests was clay-treated and then redoped with FSII and Hitec E-515. Sparking was not observed in tests with this base fuel. In the first instance it was attempted to increase the water content of the fuel by injecting water immediately upstream of the pump while fuel was circulated through the system. These attempts failed owing to the water settling out in the relaxation tank and the foam acting as a coalescer, causing water to collect in the bottom of the simulated aircraft tank. Adding a surfactant to the fuel did not alleviate the problem.

Thus, the presence of free water in the fuel was simulated by injecting a pre-emulsified mixture of fuel and water (from a tube positioned alongside the inlet) continuously throughout a test in parallel with the main fuel flow. Prior to each test, the water content of the fuel was measured with a Karl Fischer apparatus. This did not exceed 40 ppm v, illustrating the ease with which the fuel shed the free water injected during each test. Water injections up to 800 ml were examined. Although electric field readings indicated that the rate of charge generation did increase with water content, sparking was not observed in any test. Thus water did not behave as an active pro-charger.

Table B1

Nozzle: Single-orifice   Foam: Red   Fuel: Odourless kerosine

Test no.	Filling rate, USgal min^{-1}	Inlet velocity, ft s^{-1}	Fuel conductivity, pS m^{-1}	Fuel temp., °C	Peak field, kV m^{-1}	Peak nozzle current, 10^{-8} A
R1	80	10	0.85	20	4.1	0.88
R2		40			4.7	1.02
R3	70	57			5.2	0.88
R4	50	40			3.9	0.53
R5	80	40			4.5	1.00
R6	120	40			6.2	1.33

Table B2

Nozzle: Single-orifice   Foam: Coarse blue   Fuel: Odourless kerosine

Test no.	Filling rate, USgal min^{-1}	Inlet velocity, ft s^{-1}	Fuel conductivity, pS m^{-1}	Fuel temp., °C	Peak field, kV m^{-1}	Peak nozzle current, 10^{-8} A
CB1	80	10	0.93	21	47	6.9
CB2		27			55	6.2
CB3		40			62	5.2
CB4	70	57	0.95		57	3.2
Fuel clay-treated						
CB5	50	40	0.65	23	61	4.45
CB6	80		0.75		72	6.1
CB7	120		0.79		77	-

Table B3

Nozzle: Showerhead Foam: Coarse blue Fuel: Odourless kerosine

Test no.	Filling rate, USgal min^{-1}	Fuel conductivity, pS m^{-1}	Fuel temp., °C	Peak nozzle current, 10^{-7} A	No. of sparks	Max. spark size, nC
CB8	50	1.2	28	3.3	19	31
CB9				2.6	35	35
Fuel clay-treated						
CB10	50	0.46	24	3.6	80	37
CB11				4.6	100	37
CB12		0.47		4.6	97	37
CB13	80	0.48		4.6	54	38
CB14				4.2	36	28
CB15				5.2	0	-
CB16				5.0	6	30
CB17	50			2.8	1	28
CB18				3.2	4	22
CB19	80			5.2	9	32
CB20	120		25	7.0	20	30
CB21				6.0	16	34
CB22				6.1	22	38
CB23	50			3.2	0	-
CB24				3.4	0	-
System left overnight						
CB25	50	0.97	19	6.8	0	-
CB26				3.0	0	-
CB27				5.8	0	-
CB28				7.8	0	-
CB29		0.73		6.7	0	-
CB30				7.0	0	-
CB31	80		20	8.3	0	-
CB32				8.8	0	-
CB33				8.4	0	-
CB34				6.8	0	-
CB35	100	0.64		7.8	0	-
CB36				8.4	0	-
CB37	120	0.61		8.6	0	-
CB38				9.6	0	-
CB39				9.6	0	-
CB40				9.2	0	-

Table B4

Nozzle: Showerhead Foam: Red Fuel: Odourless kerosine

Fuel conductivity: 0.77 pS m^{-1}

Fuel temperature : 24°C

Test no.	Filling rate, USgal min^{-1}	Peak nozzle current, 10^{-7} A
R7	50	0.88
R8		0.95
R9		0.92
R10		0.92
R11	80	1.13
R12		1.14
R13		1.10
R14	100	1.20
R15		1.20
R16		1.20
R17	120	1.40
R18		1.45
R19		1.35

Table B5

Nozzle: Piccolo **Foam: Fine blue** **Fuel: Odourless kerosine containing FSII and Hitec E-515**

Test no.	Filling rate, USgal min^{-1}	Fuel conductivity, pS m^{-1}	Fuel temp., °C	Peak field, kV m^{-1}	No. of incendive sparks	Maximum spark size, nC	Comments
B10	44	3.0	24.5	-510	0	0	
B11			24.4	-499	0	0	
B12	80			-625	0	0	
B13				-673	0	-16	
B14		3.2		-632	0	-30	
B15	90			-632	0	-30	
B16				-653	0	-50	
B17		3.9	21.2	-632	0	-28	System left overnight
B18				-530	0	-42	
B19				-612	0	-19	
B20	86	3.7	21.6	-561	0	-22	
B21	73			-479	0	-7	
B22	60		22.0	-428	0	0	
B23				-434	0	0	
B24	67	3.6		-434	0	-2	

Table B6

Nozzle: Showerhead   Foam: Fine blue
Fuel: Odourless kerosine containing FSII and Hitec E-515

Test no.	Filling rate, USgal min^{-1}	Fuel conductivity, pS m^{-1}	Fuel temp., °C	Peak field, kV m^{-1}	No. of incendive sparks	Max. spark size, nC
B26	50	4.9	21.2	+24	No sparks observed	
B27				+42		
B28	63			+64		
B29				+74		
B30	82			+108		
B31				+126		
B32		5.0	22.2	-		
B33	104			+100		
B34	106	4.8	22.4	+95		
B35	125			+102		
B36	118	5.0	22.6	+105		
B37	83			+108		

Table B7

Nozzle: Single-orifice   Foam: Fine blue   Fuel: Odourless kerosine containing FSII and Hitec E-515

Test no.	Filling rate, USgal min^{-1}	Inlet velocity, ft s^{-1}	Fuel conductivity, pS m^{-1}	Fuel temp., ^{o}C	Peak field, kV m^{-1}	No. of incendive sparks	Max. spark size, nC	Comments
B38	120	40	6.2	20.1	-234	No sparks observed		Fuel directed against wall
B39					-261			
B40			6.3	20.2	-			
B41					-296			Fuel directed into foam
B42	80		5.9	20.6	-194			
B43					-218			
B44			5.8	21.0	-235			Fuel directed against wall
B45					-238			
B48	50				-124			
B49					-136			
B50	75	61			-			
B51	65	53	6.3		-			
B52	69	56			-			
B53			6.5		-			Fuel directed into foam
B54	71	58			-98			

Table B8

Nozzle: Single-orifice Foam: Fine blue Fuel: Odourless kerosine

Test no.	Filling rate, USgal min^{-1}	Inlet velocity, ft s^{-1}	Fuel conductivity, pS m^{-1}	Fuel temperature, ^{o}C	Peak field, kV m^{-1}	No. of incendive sparks	Maximum spark size, nC	Comments
B55	69	57	0.78	28	-255	No sparks observed		Fuel clay-treated
B56	80	40			-316			
B57	120				-408			
B58			1.9	27.1	-316			0.01 ppm ASA-3 added
B59					-367			
B60			3.8	26.0	-296			0.01 ppm ASA-3 added
B61					-371			
B62			4.5	25.8	-388			
B63					-326			
B64			5.7		-316			0.02 ppm ASA-3 added
B65					-306	0	>+35	Foam block placed opposite nozzle
B66			7.3		-235	0	>+62	0.02 ppm ASA-3 added
B67					-306	No sparks observed		Foam block removed
B68			12.5		-265			0.02 ppm ASA-3 added
B69					-306			
B70					-			
B71					-224	0	>+34	Foam block placed opposite nozzle
B72			19.4	21.2	-224	Many sparks, size unknown		0.04 ppm ASA-3 added
B73					-279	0	>+54	Foam block opposite nozzle
B74					-136	No sparks observed		Foam block removed
B75					-156			
B76			33	22.0	-33			0.16 ppm ASA-3 added
B77					-184	0	>-14	Foam block opposite nozzle
B78					-170	0	>-20	
B79					-170	0	Not recorded	
B80					-173	0	>+60	
B81					-37	No sparks observed		Foam block removed
B82			64	22.2	-10			0.16 ppm ASA-3 added
B83					-	0	>+44	Foam block opposite nozzle
B84			79	22.5	-34	0	>+37	0.16 ppm ASA-3 added
B85					-34	0	>+33	
B87	80				-16	0	>+50	
B88	76	62			-41	0	>+42	
B89	72	58	42	24.8	-139	0	>-62	Fuel clay-treated
B90			37		-163	0	>+62	Foam block opposite nozzle
B91	76	62	30	25.6	-241	0	>+75	Fuel clay-treated
B92	74	60	64	20.0	-54	0	>+46	System left over weekend
B93	72	58	21	24.2	-241	2	>+77	Fuel clay-treated
B94					-241	1	>-88	
B95					-	No sparks observed		Foam block removed
B96			17	25.6	-292	2	>-176	Fuel clay-treated
B97			10	25.2	-303	0	>+72	Foam block replaced
B98			7.4	27.0	-245	2	>+83	
B99				25.4	-408	2	>+99	Fuel clay-treated
B100			4.7	31.4	-714	0	>+77	

Table B9

Nozzle: Showerhead   Foam: Fine blue   Fuel: Odourless kerosine

Test no.	Filling rate, USgal min^{-1}	Fuel conductivity, pS m^{-1}	Fuel temp., ^{o}C	Peak field, kV m^{-1}	No. of incendive sparks	Max. spark size, nC	Comments
B101	120	5.3	25.6	+187	1	+154	
B102				+241	0	+50	
B103	80			+224	0	+62	
B104				+238	2	+187	
B105	120	5.7	25.4	-	1	+220	0.02 ppm ASA-3 added
B106				+231	6	+418	
B107				+265	2	+198, 242	
B108		7.9		+241	5	+264	System left overnight
B109	80	10	25.2	+316	1	+176	0.04 ppm ASA-3 added
B110	120			+265	No sparks observed		
B111				+296	1	+165	
B112	80	15.8	25.5	+245	No sparks observed		0.04 ppm ASA-3 added
B113	120			+204			
B114				+235			
B115		1 .0	27.0	+306	0	+88	Fuel clay treated
B116	80	7.7	28.0	+367	16	+341	
B117	120	3.5		+347	4	+374	
B118	80		25.6	+316	24	+352	
B119	120			+357	8	+385	

Table B10

Nozzle: Piccolo   Foam: Fine blue   Fuel: Odourless kerosine

Test no.	Filling rate, USgal min^{-1}	Fuel conductivity, pS m^{-1}	Fuel temp., °C	Peak field, kV m^{-1}	No. of incendive sparks	Max. spark size, nC	Comments
B120	90	2.6	29	-241	0	-39	
B121				-275	0	-55	
B122				-255	0	-17	RH = 54%
B123		5.0	27	-214	0	-66	0.02 ppm ASA-3 added
B124				-207	0	-22	
B125		5.2		-207	0	-11	0.02 ppm ASA-3 added
B126				-224	0	-28	
B127		7.6		-207	No sparks observed		0.04 ppm ASA-3 added
B128				-235			
B129		20		-37			0.08 ppm ASA-3 added
B130				-44			

Table B11

Nozzle: Piccolo   Foam: Fine blue   Fuel: Odourless kerosine

Test no.	Filling rate, USgal min^{-1}	Fuel conductivity, pS m^{-1}	Fuel temp., °C	Peak field, kV m^{-1}	No. of incendive sparks	Max. spark size, nC	Comments
B131	90	1.9	29	-238	Scope not functioning		RH = 45% Clean fuel
B132				-204			
B133				-184			
B134				-224	0	-38	
B135				-211	0	-58	
B136		5.4		-255	0	-36	0.02 ppm Stadis 450 added
B137				-184	0	-62	
B138		7.7	28	-194	0	-60	0.02 ppm Stadis 450 added
B139				-241	0	-66	
B140		16	29	-133	0	-12	0.04 ppm Stadis 450 added
B141				-162	0	-19	
B142		20		-102	No sparks observed		0.02 ppm Stadis 450 added
B143				-109			

Table B12

Nozzle: Showerhead   Foam: Fine blue   Fuel: Odourless kerosine

Test no.	Filling rate, USgal min^{-1}	Fuel conductivity, pS m^{-1}	Fuel temperature, °C	Peak field, kV m^{-1}	No. of incendive sparks	Max. spark size, nC	Comments
B144	80	1.7	25	>+340	17	>+216	Clean fuel RH = 43%
B145				+408	16	>+408	
B146	120			+479	14	>+864	
B147	80	3.0		+439	3	+300	0.01 ppm Stadis 450 added
B148	120			+449	11	+552	
B149	80			+459	8	+624	
B150		7.0	26	+357	No sparks observed		0.02 ppm Stadis 450 added
B151	120			+449	8	+240	
B152	80			+418	6	+264	
B153		9.7		+337	1	+180	0.02 ppm Stadis 450 added
B154	120			+418	1	+168	
B155	80	21.0		+265	No sparks observed		0.04 ppm Stadis 450 added
B156	120			+357			

Table B13

Nozzle: Showerhead   Foam: Promel   Fuel: Odo[illegible]less kerosine

Test no.	Filling rate, USgal min^{-1}	Fuel conductivity, pS m^{-1}	Fuel temp., ^oC	Peak field, kV m^{-1}	No. of incendive sparks	Max. spark size, nC	Comments
P1	80	2.5	32	+31	No sparks observed		Clean fuel
P2	120			+30			RH = 45%
P3	80	4.8		+48			0.01 ppm Stadis 450 added
P4	120			>+102			
P5	80	5.4	31	+85			0.01 ppm Stadis 450 added
P6	120			+153			
P7	80	7.1		+133			0.02 ppm Stadis 450 added
P8	120			+224			
P9	80	14.0	30	+105			0.04 ppm Stadis 450 added
P10	120			+218			
P11	80	22.0		+65			0.04 ppm Stadis added
P12	120			+173	0	+14	Several ~ +6nC sparks observed
P13		31		+133	0	+12	
P14		24	22	+114	No sparks observed		System left overnight
P15		30		+122			0.04 ppm Stadis 450 added
P16	80			+51			

Table B14

Nozzle: Showerhead Foam: Fine blue Fuel: Odourless kerosine and polysulphone

Test no.	Filling rate, USgal min^{-1}	Fuel conductivity, pS m^{-1}	Fuel temperature, °C	Peak field, kV m^{-1}	No. of incendive sparks	Max. spark size, nC	Comments
B157	80	1.2	22.5	+170	0	+10	Clean fuel RH = 52% at 22°C
B158	120			+240	No sparks observed		
B159				+173	0	+12	
B160				+150	0	-10	
B161	80	1.4	23.0	+105	No sparks observed		0.005 ppm polysulphone added
B162	120			+135	0	-22	
B163	80	2.6	23.5	+173	3	>+360	0.0012 ppm polysulphone added
B164	120			+203	4	+550	
B165	80	3.7	24.0	+233	21	>+750	0.02 ppm polysulphone added
B166	120			+293	21	+1050	
B167				+307	25	+820	
B168	80			+293	23	+1090	
B169		5.9		+293	31	>+1330	0.04 ppm polysulphone added
B170				+300	34	+1330	
B171				+248	22	+1014	
B172	120			+345	>16	+1090	
B173				+360	>20	>+1330	
B174				+330	35	+1480	
B175	80	3.6	22.5	+353	46	+1200	0.01 ppm ASA-3 added
B176	120			+413	29	+940	
B177				+473	30	+940	
B178	80			+390	44	+1380	
B179		4.2	23.0	+383	37	+1270	0.04 ppm ASA-3 added
B180	120			+412	33	+1100	
B181	80			+390	38	+1100	
B182		5.3	24.5	+345	26	+880	0.06 ppm ASA-3 added
B183	120			+450	35	+770	
B184	80	7.0	25.0	+375	26	+605	0.04 ppm ASA-3 added
B185	120			-	20	+660	
B186	80	14.4	25.5	+270	2	+220	0.06 ppm ASA-3 added
B187	120			+338	1	+264	
B188				+293	No sparks observed		
B189	80			+300		"	
B190				+308	1	+154	
B191		15.0		+285	2	+198	0.02 ppm ASA-3 added
B192		20.0	25.0	+255	No sparks observed		0.04 ppm ASA-3 added
B193				+165			
B194	120			+233			
B195	80			+210			

Table B15

Nozzle: Showerhead   Foam: Fine blue   Fuel: Odourless kerosine and polysulphone

Test no.	Filling rate, USgal min^{-1}	Fuel conductivity, pS m^{-1}	Fuel temp., °C	Peak field, kV m^{-1}	No. of incendive sparks	Max. spark size, nC	Comments
B196	80	1.0	23.4	+368	13	+1100	Clay-treated fuel RH = 46% at 23°C
B197		2.6		+338	37	+1540	0.02 ppm polysulphone added
B198				+383	32	+1650	
B199		3.7	24.0	+360	39	+1540	0.02 ppm polysulphone added
B200				+353	43	>+1930	
B201		4.2	25.0	+405	45	+1610	0.01 ppm Stadis 450 added
B202				+375	50	+1540	
B203		9.3	25.5	+375	47	+1210	0.02 ppm Stadis added
B204				+375	51	+990	
B205				-	48	+1100	
B206		16.0		+390	40	+940	0.02 ppm Stadis added
B207				+405	42	+990	
B208		20.0	26.0	-	24	+550	0.02 ppm Stadis added
B209					26	+594	
B210		24.0		+412	12	+506	0.02 ppm Stadis added
B211		37.0	25.5	+255	No sparks observed		0.04 ppm Stadis added
B212				+278			
B213				+225			

Table B16

Nozzle: Single-orifice   Foam: Fine blue   Fuel: Odourless kerosine

Test no.	Filling rate, USgal min^{-1}	Inlet velocity, ft s^{-1}	Fuel conductivity, pS m^{-1}	Fuel temp., °C	Peak field, kV m^{-1}	No. of incendive sparks	Max. spark size, nC	Comments
B214			1.8	23.5	-90	0	>+90	Base fuel
B215					-60	0	>+110	RH = 43% at 23.5°C
B216					-	16	>+370	0.06 ppm polysulphone added
B217			4.5	23.0	-165	11	>+605	
B218					-120	7	>+462	
B219					-255	50	>+750	0.04 ppm polysulphone added
B220				24.0	-195	41	>+750	
B221			7.1		-120	104	>+750	Foam block opposite nozzle removed
B222				25.5	-75	96	>+750	0.02 ppm ASA-3 added
B223					-150	31	>+750	Foam block replaced
B224			9.3	26.0	-128	17	>+420	0.04 ppm ASA-3 added
B225					-50	38	>+750	Foam block removed
B226	72	58	10.0		-75	35	>+750	0.02 ppm ASA-3 added
B227			15.0	27.0	-68	30	>+750	0.04 ppm ASA-3 added
B228					-168	24	>+750	Foam block replaced
B229			39.0	24.0		0	>+44	System left overnight
B230						0	>+22	
B231								Foam block removed
B232						No sparks observed		
B233			42	24.5	>-75			0.08 ppm ASA-3 added
B234					-100	0	>+28	Foam block replaced
B235			50	26.0	-93	0	-	0.08 ppm ASA-3 added
B236					-103	0	>+22	
B237					-43	No sparks observed		Foam block removed
B238					-	0	>+11	Foam block replaced
B239			83		-15	0	>+3	0.16 ppm ASA-3 added
B240					-	0	>+11	RH = 57% at 23°C
B241	80	40			-	0	>+15	Inlet velocity reduced
B242		36	155	29	-	0	>+5	0.32 ppm ASA-3 added
B243		58			-	0	>+3	
B244	72	24			-	0	>+3	
B245		9	190		-	0	>+1	
B246					-	0	>+1	0.16 ppm ASA-3 added
B247		58			-	0	>+4	

Table B17

Nozzle: Piccolo   Foam: Fire blue   Fuel: Odourless kerosine and polysulphone

Test no.	Filling rate, USgal min^{-1}	Fuel conductivity, pS m^{-1}	Fuel temp., ^{o}C	Peak field, kV m^{-1}	No. of incendive sparks	Max. spark size, nC	Comments
B248	90	0.9	24.5	-	No sparks observed		Clay-treated fuel
B249				-	0	-15	
B250		4.5	25.5	-	14	-187	0.04 ppm polysulphone added
B251				-	3	-94	
B252		5.3	26.0	-	0	-12	0.02 ppm polysulphone added
B253					No sparks observed		
B254		6.6	27.0	-			0.04 ppm polysulphone added
B255				-			
B256		9.5		-			0.04 ppm polysulphone added
B257							

Table B18

Nozzle: Piccolo   Foam: Fine blue   Fuel: Odourless kerosine containing FSII and Hitec E-515

Test no.	Filling rate, USgal min^{-1}	Fuel conductivity, pS m^{-1}	Fuel temp., °C	Peak field, kV m^{-1}	No. of incendive sparks	Max. spark size, nC	Comments
B258	90	1.0	26	-140	No sparks observed		Clean fuel
B259				-180			
B260				-195			
B261		5.0		-840	4	-210	FSII + Hitec E-515 added
B262				-473	2	-130	
B263				-473	1	-110	
B264		5.5	12.0	-431	0	-44	Temperature reduced
B265				-599	5	>-165	
B266		-	10.0	-515	7	-220	Temperature reduced
B267		5.0	6.0	-441	4	-198	Temperature reduced
B268				-441	4	-231	
B269		3.3	3.0	-	7	-167	Temperature reduced
B270				-431	3	-264	
B271		1.7	-10	-494	3	-242	Temperature reduced
B272				-452	1	-132	
B273				-473	0	-	
B274				-437	0	-	
B275				-504	3	-374	
B276				-436	2	-264	
B277		0.9	-15	-494	6	-23[illegible]	Temperature reduced
B278				-515	3	-100	
B279				-494	2	>-440	
B280		3.2	14.0	-231	0	-44	System allowed to warm up
B281				-284	0	-55	
B282				-326	0	-55	
B283		3.3	19.0	-231	No sparks recorded		
B284				-263	0	-44	
B285				-315	0	-44	

Table B19

Nozzle: Piccolo   Foam: Fine blue   Fuel: Odourless kerosine containing FSII and Hitec E-515 + polysulphone

Test no.	Filling rate, USgal min^{-1}	Fuel conductivity, pS m^{-1}	Fuel temp., ^{o}C	Peak field, kV m^{-1}	No. of incendive sparks	Max. spark size, nC	Comments
B286	90	7.4	16.0	-494	5	-154	0.011 ppm polysulphone added
B287				-483	1	-143	
B288				-483	3	-110	
B289				-483	3	-88	
B290		8.1		-567	6	-297	0.005 ppm polysulphone added
B291				-536	6	-264	
B292		11		-504	6	-154	0.01 ppm polysulphone
B293				-494	6	-220	
B294				-462	6	-286	
B295		18.5	13.0	-315	No sparks observed		0.02 ppm ASA-3 added
B296		16.0		-357			
B297				-378	1	-77	
B298		18.0	13.5	-326	No sparks observed		0.005 ppm ASA-3 added
B299				-335			
B300		12.0	3.0	-315			Temperature reduced
B301				-327			
B302				-307			
B303		8.0	-6.0	-330			Temperature reduced
B304				-345			
B305				-312			
B306		6.0	-15	-327			Temperature reduced
B307				-350			
B308				-321			

Table B20

Nozzle: Piccolo   Foam: Fine blue   Fuel: Odourless kerosine containing FSII and Hitec E-515

Test no.	Filling rate, USgal min^{-1}	Fuel conductivity, pS m^{-1}	Fuel temp., ^{o}C	Peak field, kV m^{-1}	No. of incendive sparks	Max. spark size, nC	Comments
B309	90	1.2	14.6	-315	No sparks observed		Clean fuel
B310		3.1	17.0	-242			FSII + Hitec E-515 added
B311				-231			
		20 ml H_2O injected					
B312		3.3	18.0	-231			Total water content = 26 ppm
B313				-221			
		50 ml H_2O injected					
B314		3.0	19.0	-221			Total water content = 40 ppm
B315				-273			
		100 ml H_2O injected					
B316		3.4	21.0	-315			Total water content = 30 ppm
B317				-322			
		200 ml H_2O injected					
B318		3.9	22.0	-336			Total water content = 31 ppm
		400 ml H_2O injected					
B319		3.3	16.0	-350			Total water content = 30 ppm
		800 ml H_2O injected					
B320		3.3	16.0	-347			Total water content = 27 ppm
B321				-356			

N.B. Quoted water content refers to that of the fuel in the open tank. This was determined immediately before each test.

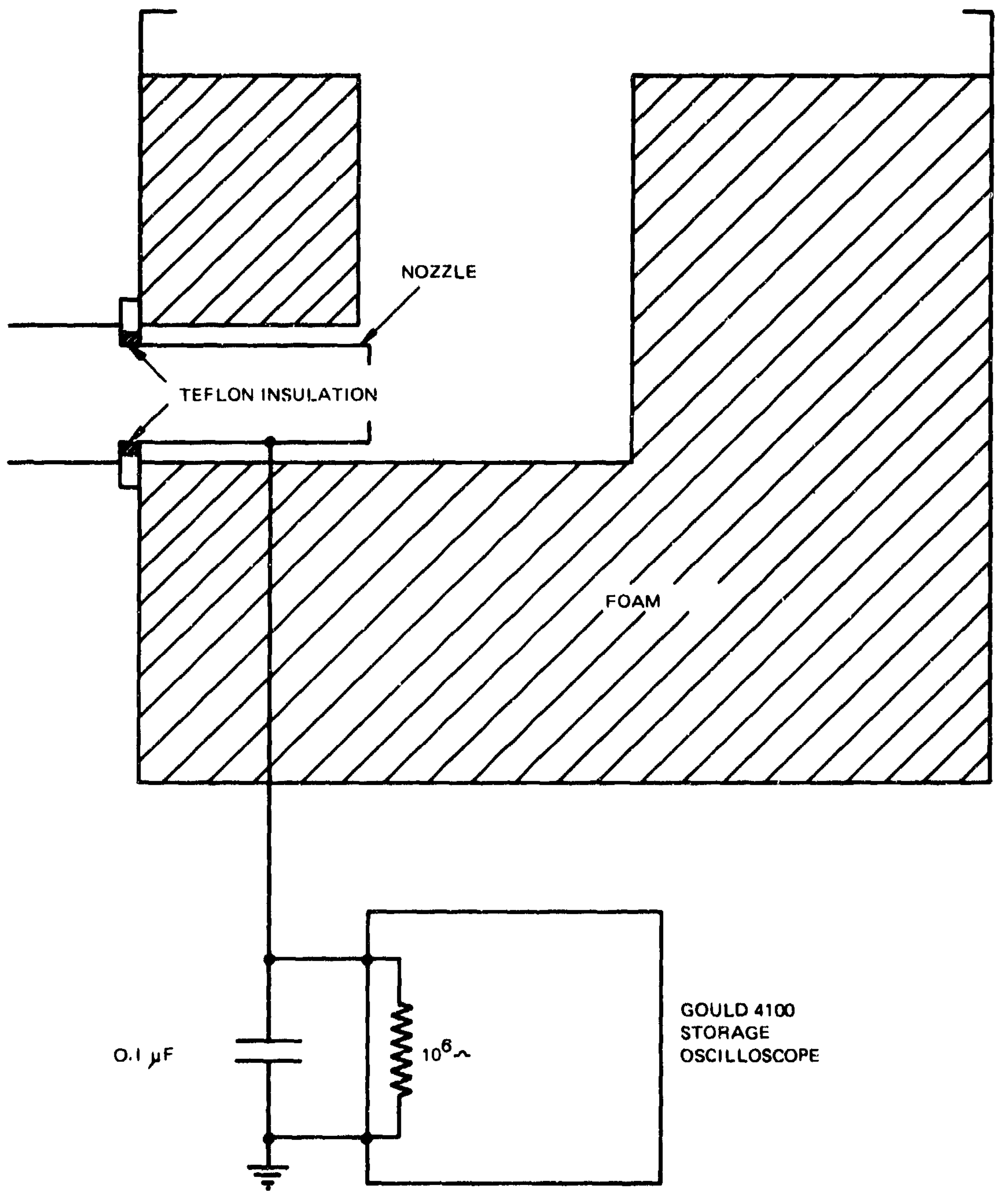


FIG. B1 — Arrangement inside test tank and measuring circuit

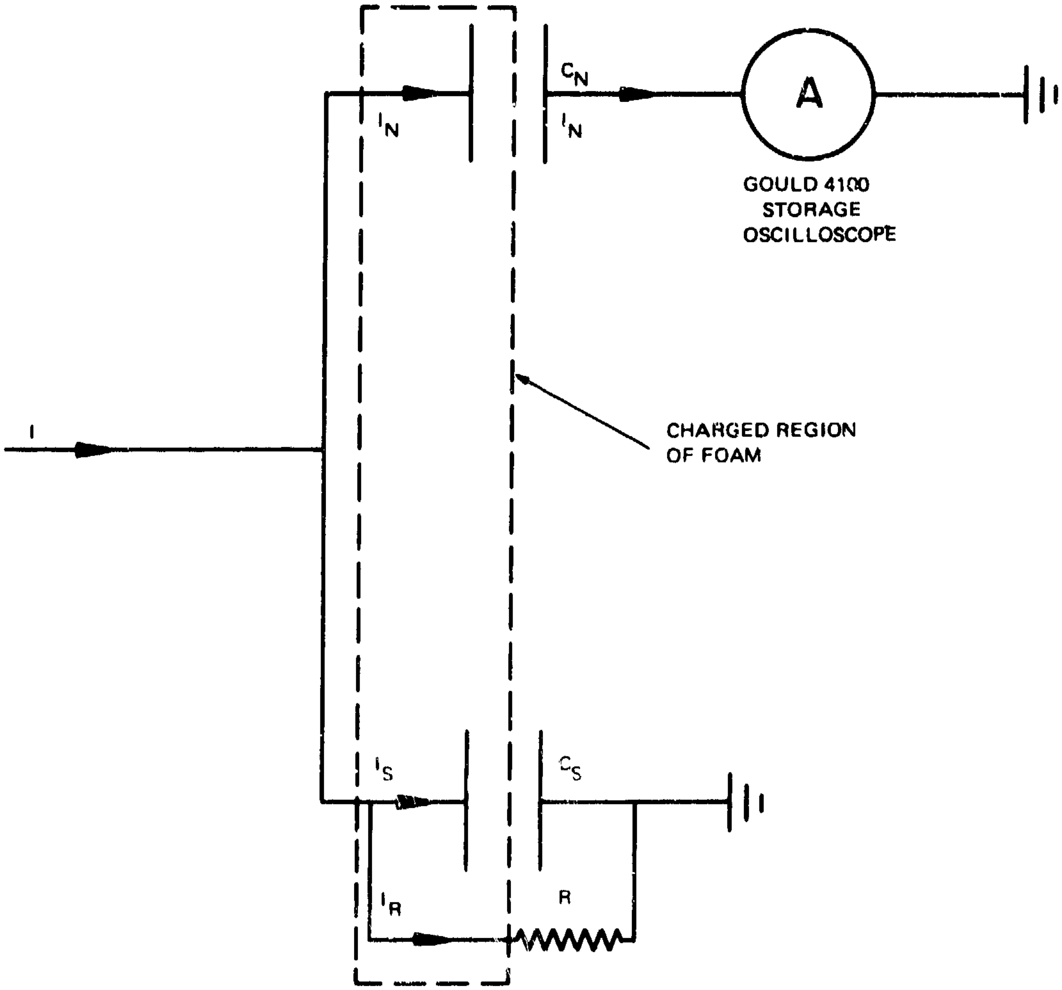


FIG. B2 — Foam charging equivalent circuit

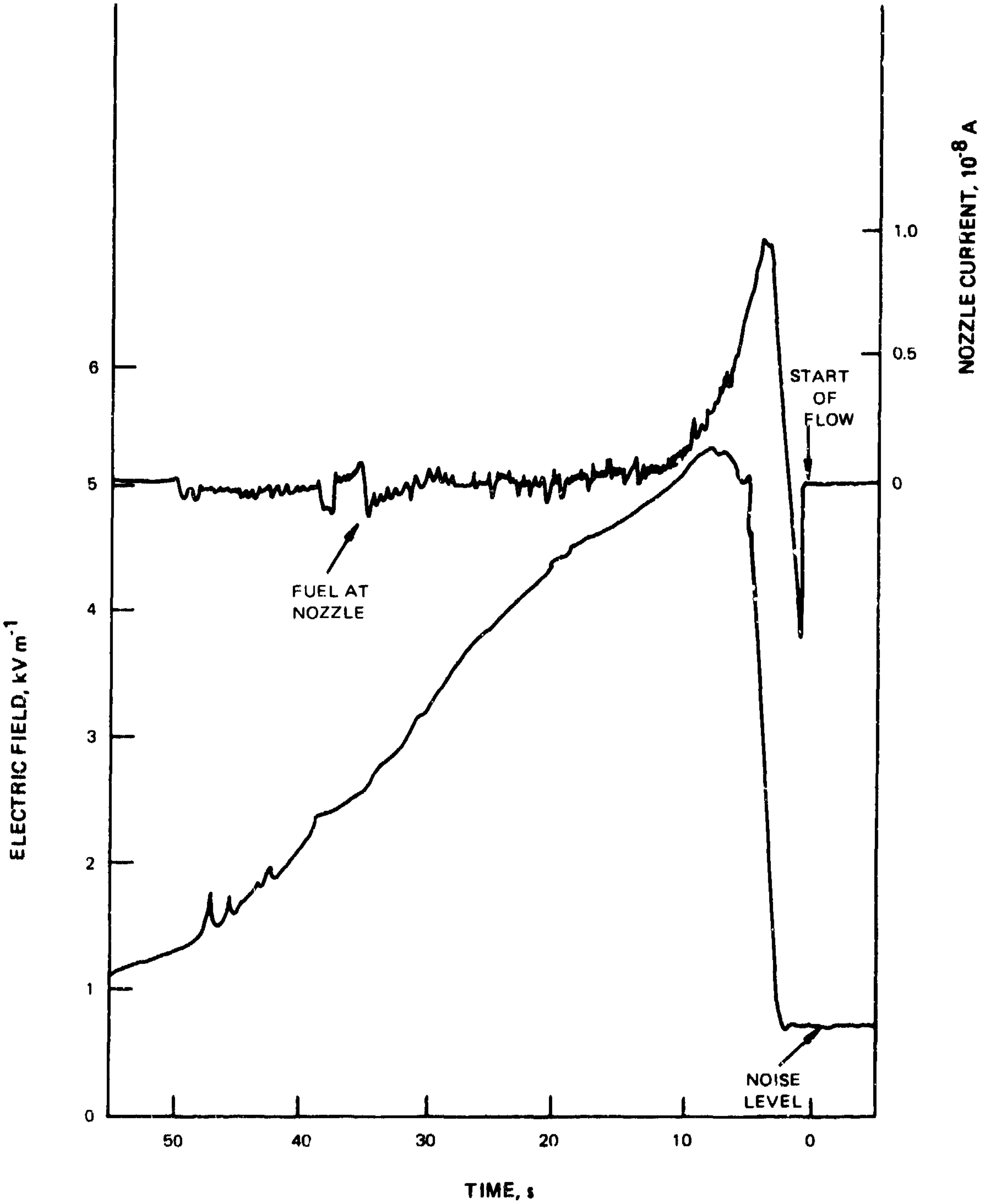


FIG. B3 — Red polyester foam test: electric field and nozzle current. Inlet velocity 40 ft s^{-1}, filling rate 80 USgal min^{-1}.

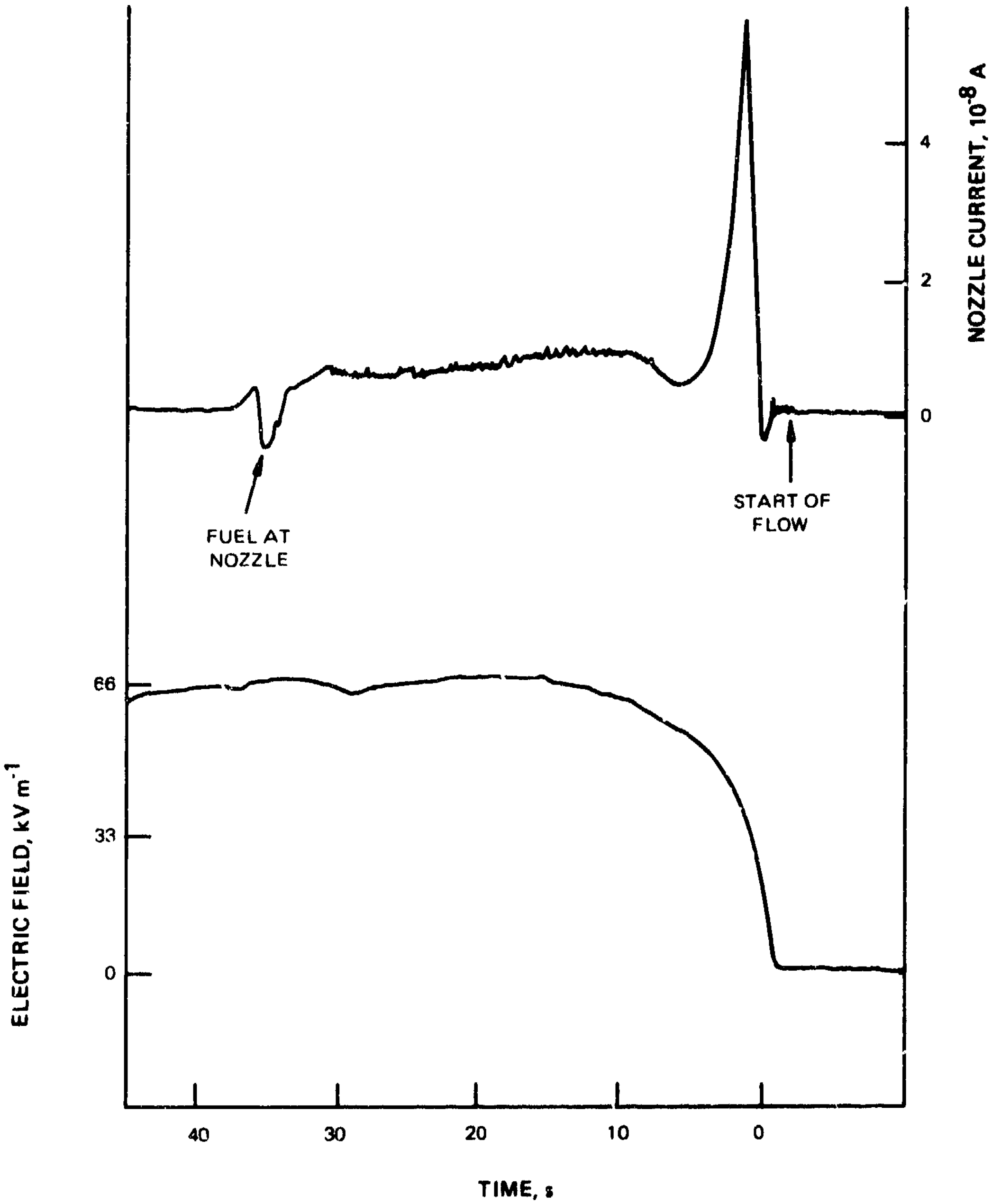


FIG. B4 — Blue polyether foam test: electric field and nozzle current. Inlet velocity 40 ft s^{-1}, filling rate 60 USgal min^{-1}.

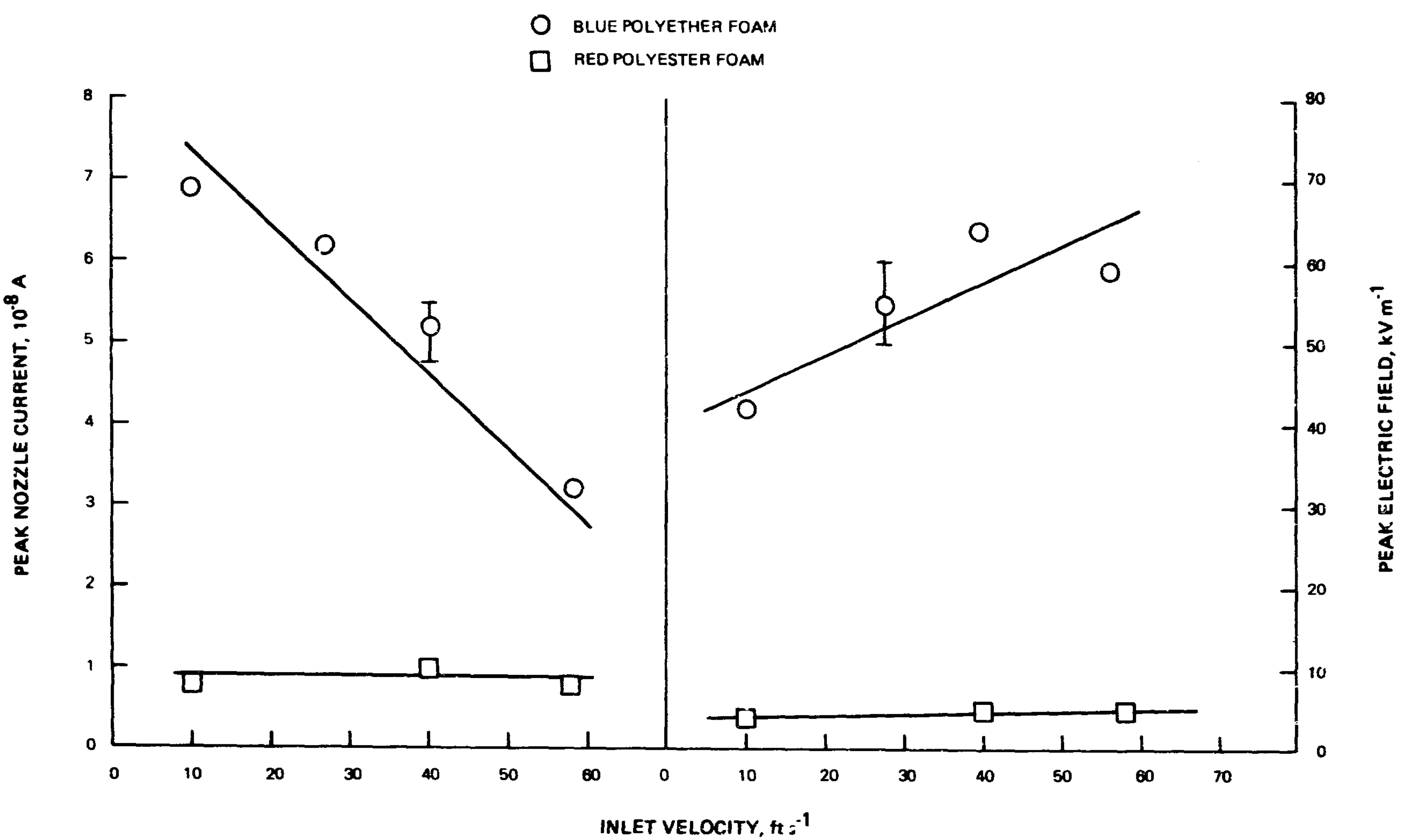


FIG. B5 – Variation of rate of charge generation with inlet velocity. Filling rate 80 USgal min^{-1}

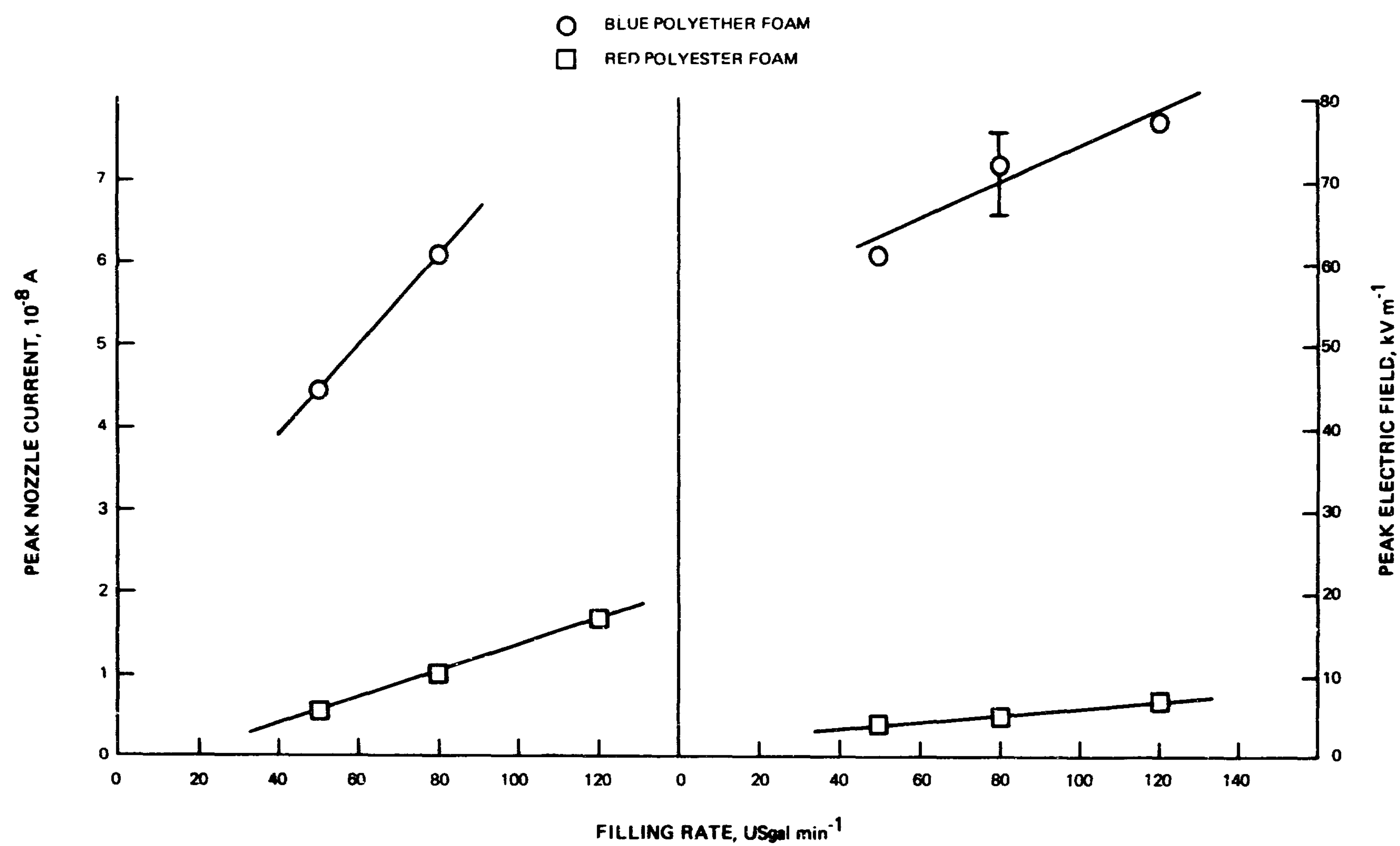


FIG. B6 — Variation of rate of charge generation with filling rate. Inlet velocity 40 ft s^{-1}

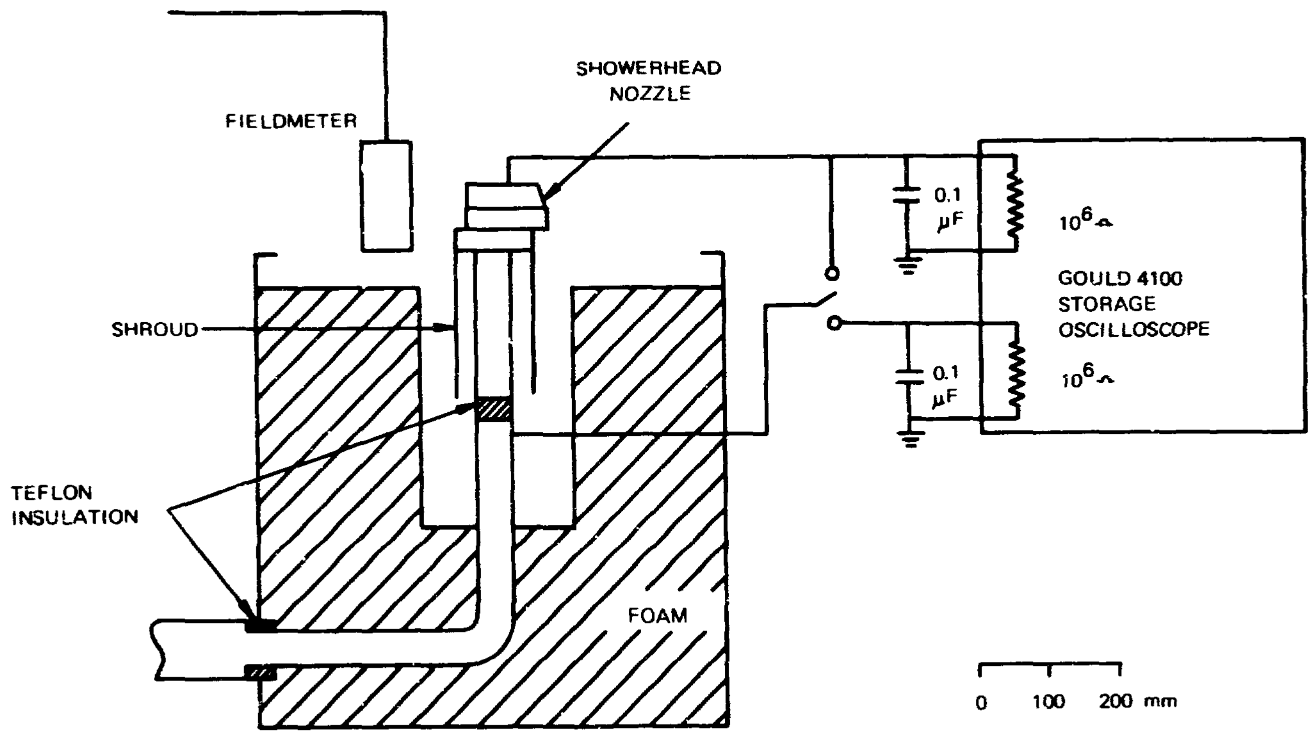


FIG. B7 — Arrangement for tests with showerhead nozzle

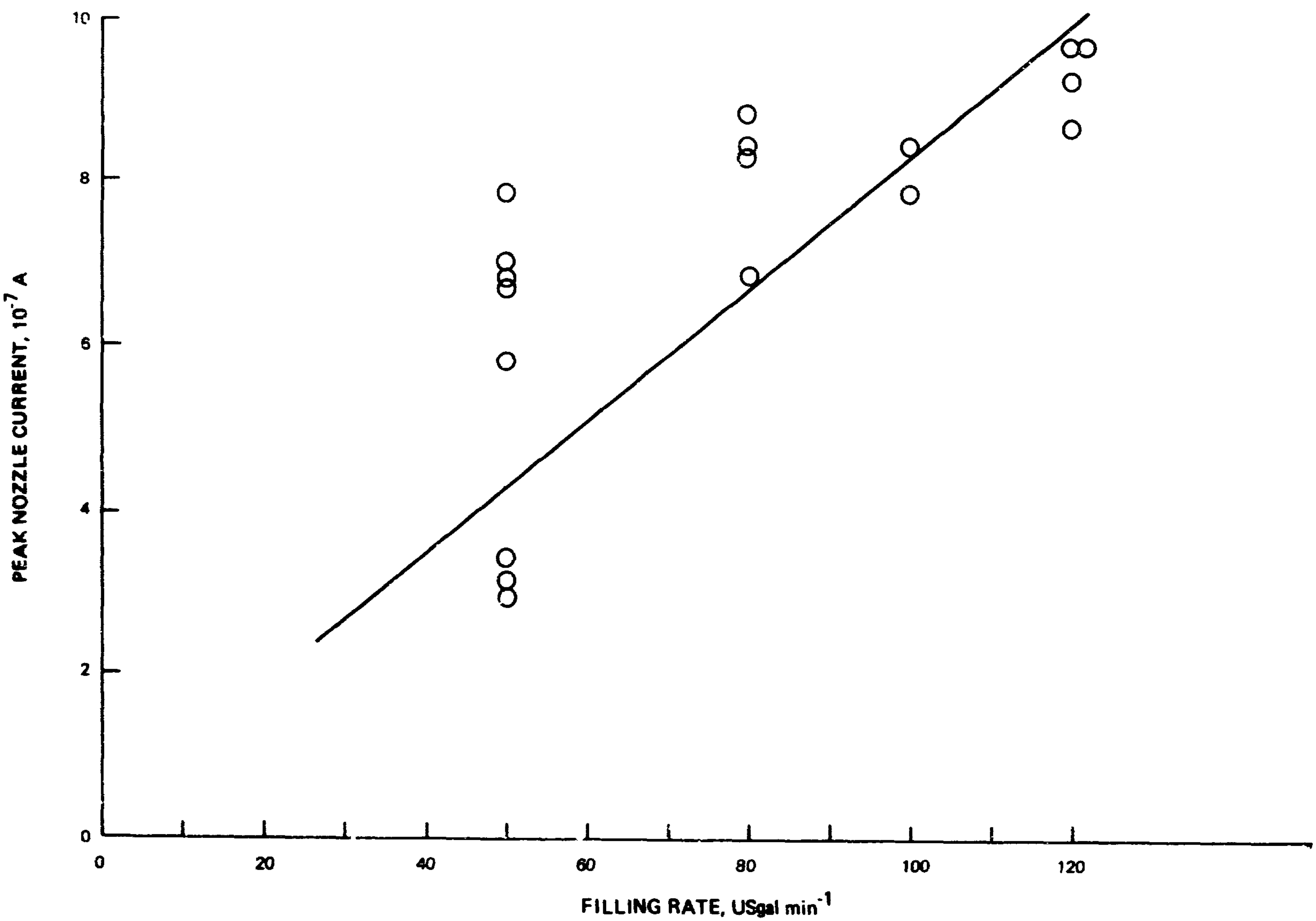


FIG. B8 — Results from tests with showerhead nozzle and blue polyether foam

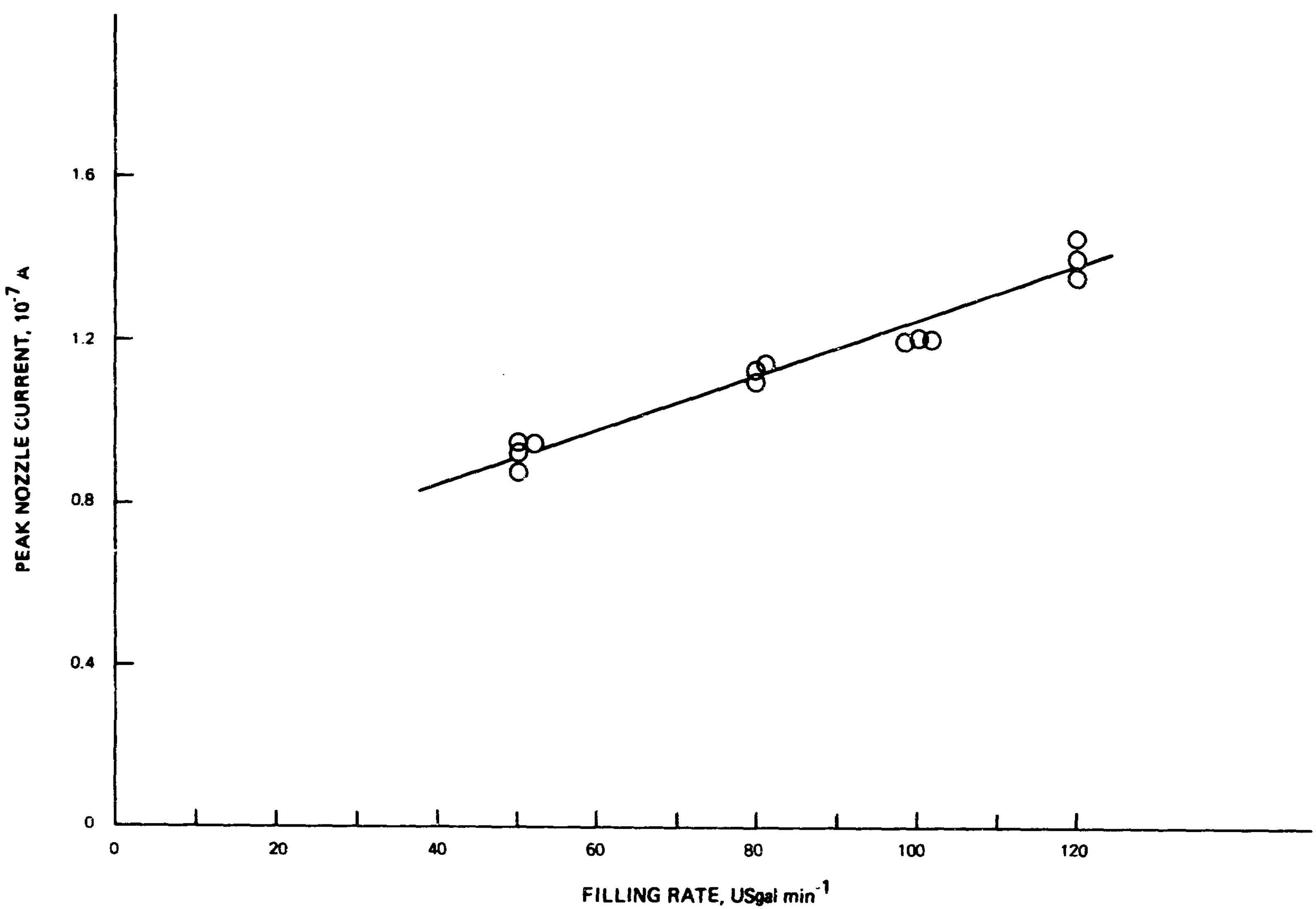


FIG. B9 — Results from tests with showerhead nozzle and red polyester foam

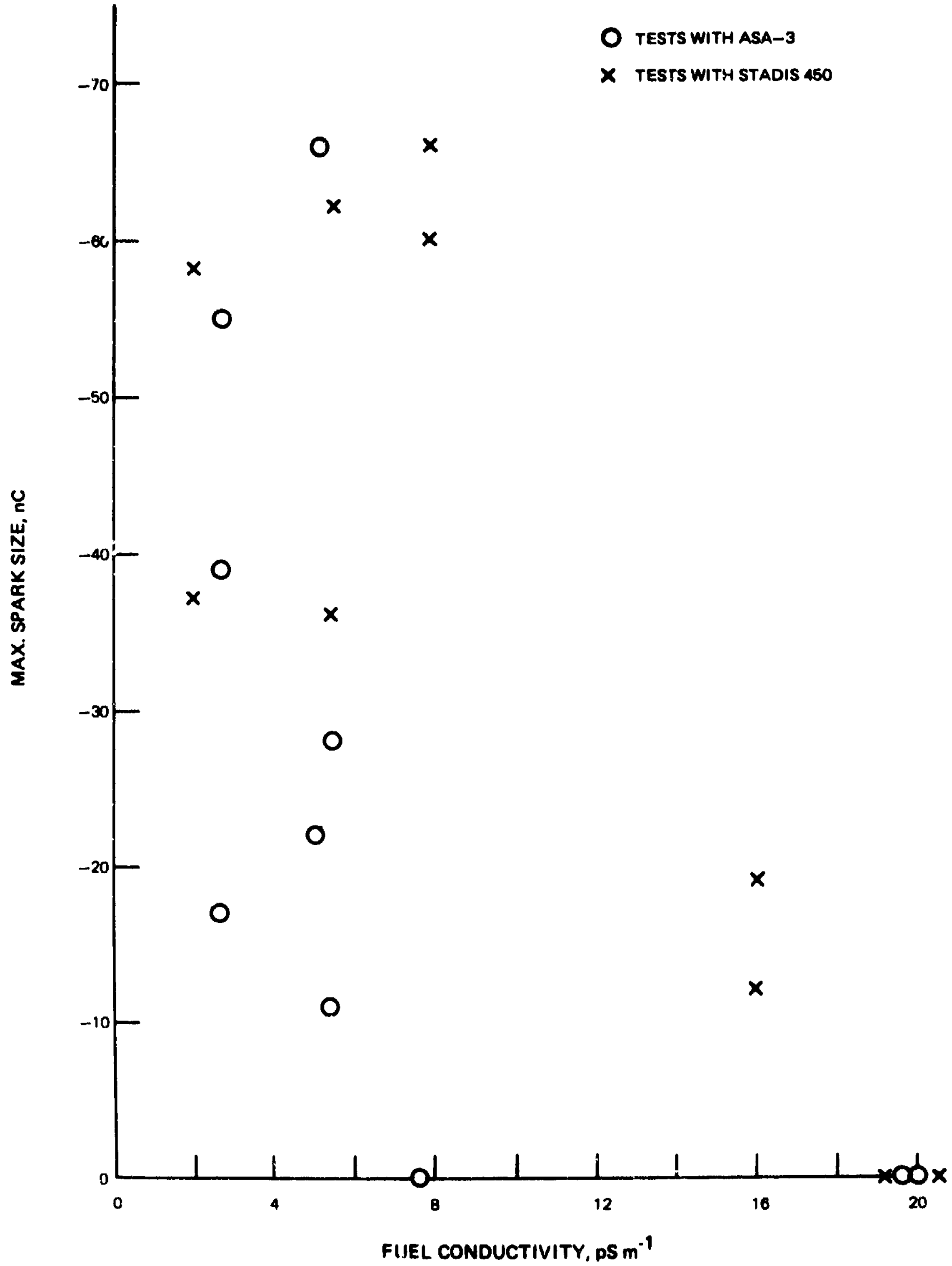


FIG. B10 — Tests with piccolo nozzle and ASA–3 and Stadis 450

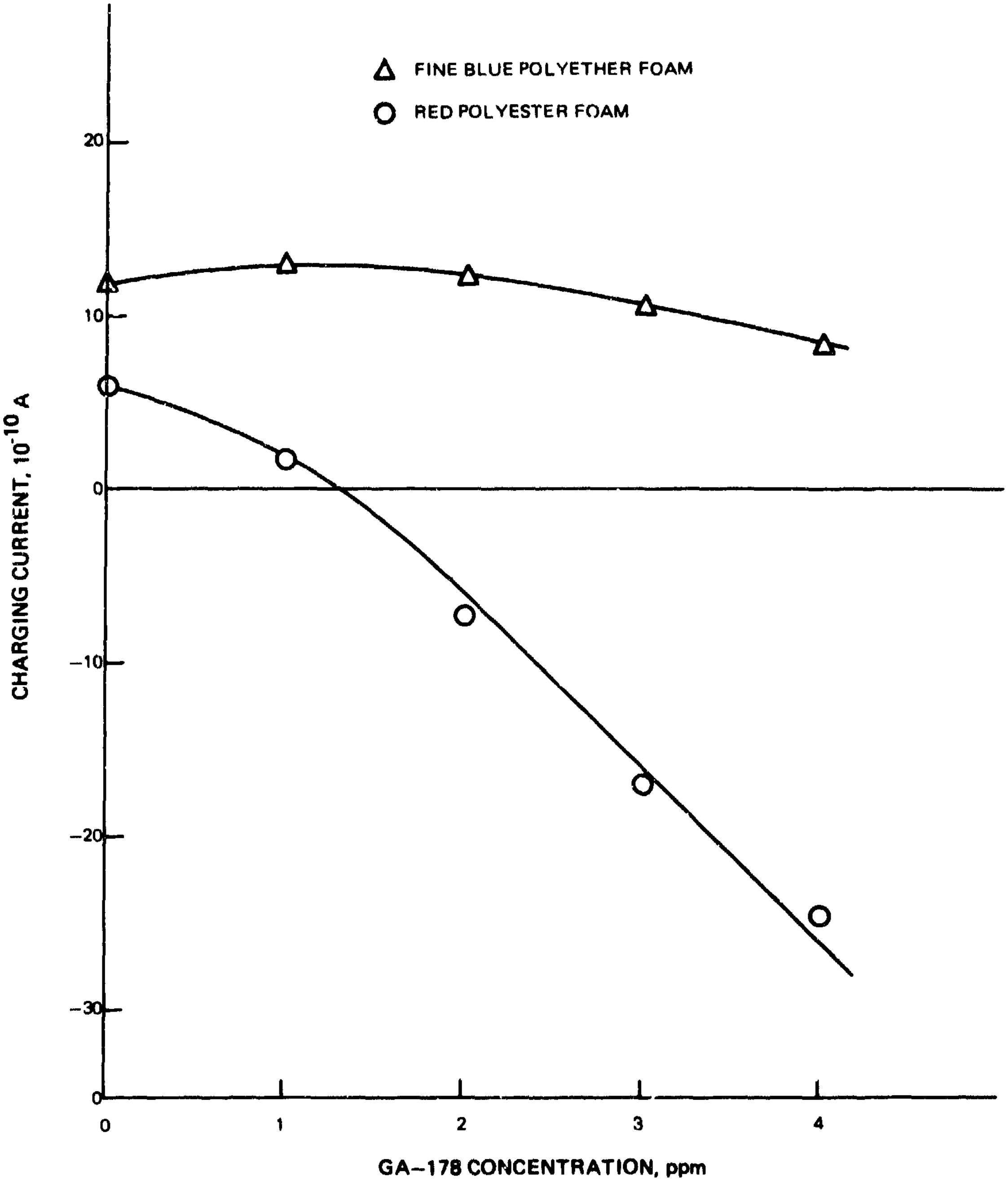


FIG. B11 — Charging tendency of GA−178

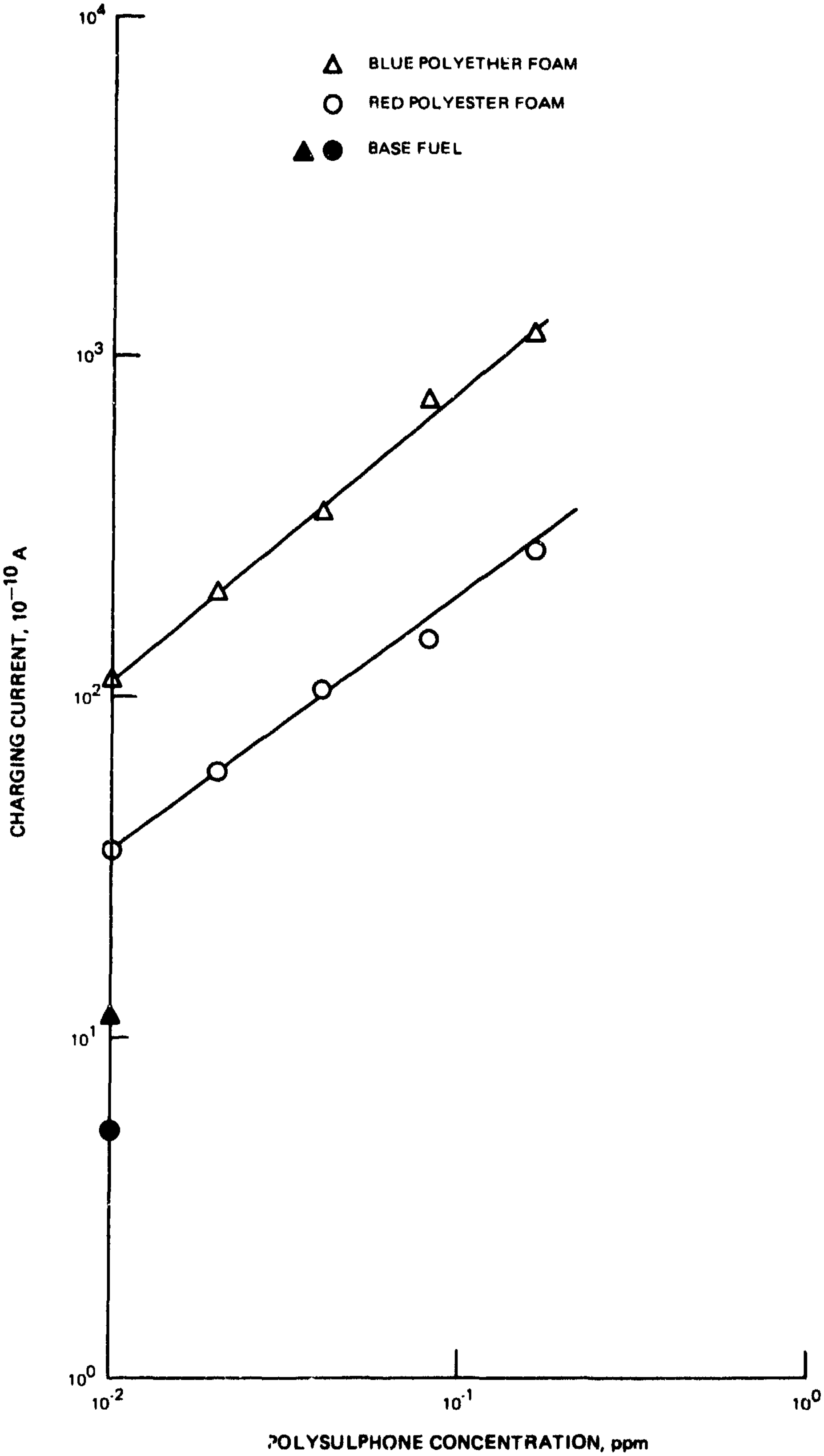


FIG. B12 – Charging tendency of polysulphone

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